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EPR BURNABLE ABSORBER OPTIMIZATION

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ČVUT
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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní obor: **Jaderná energetická zařízení**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Optimalizace vyhořívajících absorbátorů pro reaktor EPR

Název diplomové práce anglicky:

EPR burnable absorber optimisation

Pokyny pro vypracování:

1- seznamte se s kódem UWB1
2- proveďte rešerši stavu BA
3- seznamte se s reaktorem EPR
4- navrhněte BA pro EPR
5- zhodnoťte vybrané řešení

Seznam doporučené literatury:

1 UWB1 manual
2 EPR handbook
3 dle pokynů vedoucího

Jméno a pracoviště vedoucí(ho) diplomové práce:

doc. Ing. Radek Škoda, Ph.D., ústav energetiky FS

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

30.10.2017

Datum převzetí zadání Podpis studenta

Affidavit:

I hereby declare that this master's thesis has been written only by the undersigned and without any assistance from third parties, except for consultation with my supervisor and consultant.

Furthermore, I confirm that no sources have been used in the preparation of this thesis other than those indicated in the bibliography.

In Prague on ……

……

Bc. Michal Zeman

Annotation sheet

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Abstract: The research of burnable absorber (BA) is a very important issue, due to BA influence on regulation and control of reactivity in the reactor. Burnable absorbers compensate initial excess reactivity in the reactor and thus allow longer fuel cycle with higher fuel enrichment. This thesis deals with the depletion calculation of EPR nuclear fuel with different types of BA, and with optimization of the BA. The distribution of BA in the fuel is assumed uniform. Based on depletion calculation, elements are divided into two groups, the so-called fast and slow BA. Several combinations of two elements BA are then calculated based on this division. The evaluation of each BA combination is made, and the most appropriate one is selected.

Abstrakt: Výzkum vyhořívajících absorbátorů je velmi důležité téma, jelikož vyhořívající absorbátory ovlivňují regulaci a kontrolu reaktivity v reaktoru. Vyhořívající absorbátory kompenzují počáteční přebytek reaktivity v reaktoru, a proto umožňují delší palivový cyklus použitím paliva s vyšším obohacením. Tato práce se zabývá výpočtem vyhořívání jaderného paliva reaktoru EPR s různými typy vyhořívajících absorbátorů, a dále optimalizací absorbátoru pro tento reaktor. V palivu je uvažováno uniformní rozdělení vyhořívajícího absorbátoru. Jednotlivé prvky jsou rozděleny na dvě skupiny, rychlé a pomalé vyhořívající absorbátory. Na bázi tohoto rozdělení je vytvořeno a následně spočítáno několik kombinací vyhořívajícího absorbátoru složeného ze dvou prvků. Následně je provedeno vyhodnocení jednotlivých kombinací vyhořívajícího absorbátoru a zvolena nejvhodnější varianta.

Keywords: Burnable absorbers, EPR, Depletion calculation

Klíčová slova: Vyhořívající absorbátory, EPR, Výpočet vyhořívání

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Finally, I must express my gratitude to my family for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis.

Content

List of abbreviations and indexes:

R_f	Outer fuel pellet radius [cm]
R_cl	Outer cladding radius [cm]
R_cl	Inner cladding radius [cm]
P	Pitch [cm]
N_{th}	Nominal thermal power [MW]
m_u	Amount of uranium in 1 fuel assembly [MTU]
f	Number of the fuel assemblies [-]
DP	Depletion power [MW/MTU]
A	Mass number [-]
Z	Atomic number [-]
m	State of the nuclide
N_i	Nuclear density [at/bcm]
$W_{f,i}$	Weight fraction of i-th nuclide [-]
N_A	Avogadro number [at/mol·cm^2/b], N_A = 0.602214199 at/mol·cm^2/b
$A_{w,I}$	Atomic weight of i-th nuclide [g/mol]
k_{eff}	Multiplication factor [-]
ρ	Reactivity [-]
Δρ	Reactivity difference [-]
B	Burnup [MWd/MTU]
σ_c	Neutron capture cross section [b]
k_{effBA}	Multiplication factor of state with burnable absorber [-]
k_{effNAT}	Multiplication factor of state without burnable absorber [-]

1. Introduction

Nuclear fuel design is a very important and complex problem. The fuel design is preceded by series of physical, chemical, economical, and other related calculations. To design nuclear fuel with higher enrichment, lower power peaking factor and longer fuel cycles, burnable absorbers (BA) were developed. Burnable absorber serves as a compensator of the excess reactivity in the reactor throughout the operation. High compensation is required at the beginning of the fuel cycle. By contrast, at the end of the campaign, it is preferable to have zero or negative compensation (positive reactivity). Hence to prolong the fuel cycle. Burnable absorbers are very important for better regulation and control of the reactor. Properties of the burnable absorber can positively or negatively influence other materials. Therefore, a great attention should be given to the choice of the burnable absorber material. Today most of the reactors, including the EPR reactor, use Gd_2O_3 as a burnable absorber.

This diploma thesis deals with the design and optimization of the burnable absorber for the EPR reactor. The calculation was made in the UWB1 code. UWB1 is a fast depletion code used for the study of burnable absorbers. In the first part of this work burnable absorbers, their desired properties, and the basic information about EPR reactor are described. The second part deals with the UWB1 code; e.g., for which calculations it can be used, how it solves the calculations, and the description of the EPR reactor model. The third part is the calculation process itself. Here, the selection methods for initial 11 chemical elements that were evaluated as potential BA is explained as well as the initial step calculation. Further, a detailed calculation of the selected six elements, that were chosen from the initial 11, is described. The last part deals with the combination of 2 elements in BA, the combination selection method and the concentration of individual elements. A detailed calculation of such BA and the usage of 2 elements BA in 3, 4 and 5-year fuel cycle are made.

Based on these calculations, the evaluation technique was developed, and resulting combinations were evaluated. As a final part of this thesis, the most suitable burnable absorber was selected.

2. Burnable absorbers

Together with control rods and boric acid, burnable absorbers are used in a reactor to compensate excess reactivity throughout the operation. Due to the burn-up of the absorber material, the negative reactivity of the burnable absorber decreases over core life. At the beginning of nuclear power, only the first two methods, the H_3BO_3 solution in the coolant and the control rods, were used to compensate the reactivity. With the advent of burnable absorbers, it was possible to use up to 5% fuel enrichment and to configure the reactor core with minimum neutron leakage (i.e., fresh fuel located in the center of the reactor core). The basic idea about burnable absorber is to have large compensation at the beginning of the fuel cycle. And opposite to that at the end of the fuel cycle, the compensation should be ideally zero or negative (positive reactivity), so that the fuel cycle can be prolonged. [1]

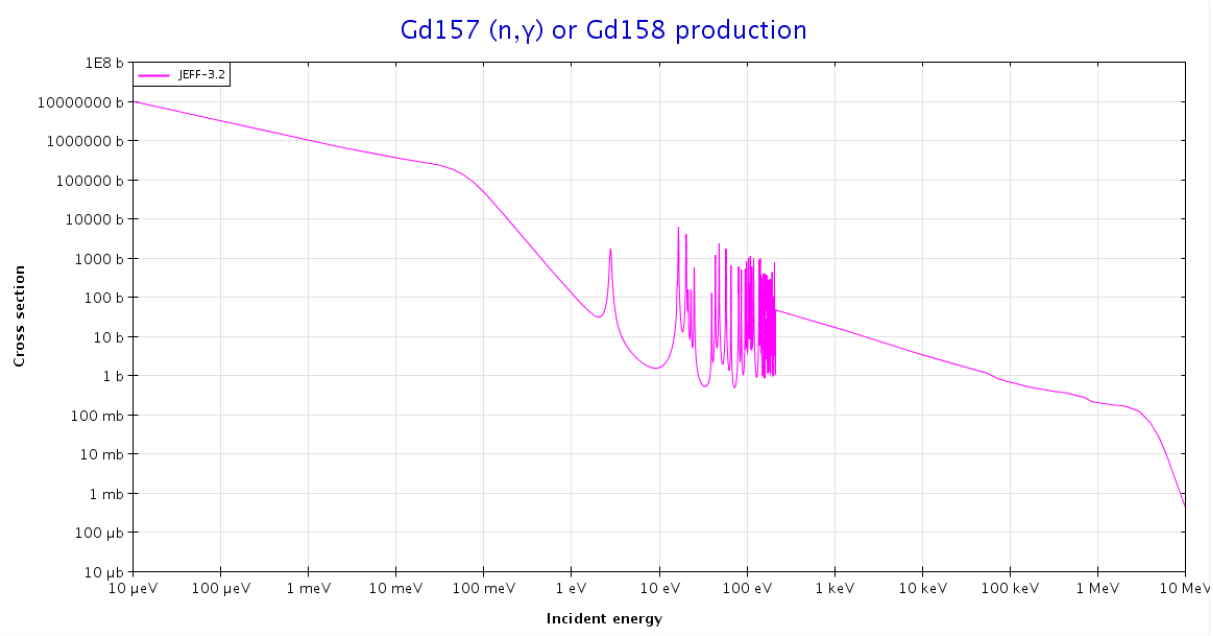
2.1 Materials for BA

A desired burnable absorber material needs to have large neutron absorption cross section. To be suitable for use as a burnable absorber, the material must, in addition to its high neutron absorption cross section, fulfill another crucial condition. The final daughter nuclide needs to have low absorption cross section. Mother nuclide, thanks to its high absorption cross section, causes neutron to be absorbed. As the neutron is absorbed, the multiplication factor decreases and therefore, the excess reactivity is compensated. Due to the fact, that nuclide resulting from neutron absorption has a lower neutron absorption cross section, the absorber is burnable, and the negative reactivity decreases with the fuel depletion. The greater the difference of cross section between mother-daughter nuclides, the faster the absorber will be burned. [1] [2]

Today the most commonly used elements are boron and gadolinium. Other elements used include erbium, cadmium, and dysprosium. Their individual isotopes have very different absorption cross-sections, so the enrichment with a particular isotope can be used. In the case of boron, the isotope ^{10}B has a natural concentration of 19.9%, which represents a sufficient proportion. For gadolinium, we are mainly interested in isotopes ^{157}Gd (15.7%) and ^{155}Gd (14.8%). Other suitable isotopes are, for example, ^{113}Cd, ^{167}Er, and ^{164}Dy. [2]

The highest probability of thermal neutron absorption is for ^{157}Gd (about 254 000 b) [3], followed by ^{155}Gd (ca. 60 900 b) [3] and ^{113}Cd (ca. 20 615 b) [3]. Other isotopes have effective cross sections to absorb thousands or hundreds of barns. [2]

In the following chart, the neutron absorption cross section for ^{157}Gd is shown.



Graph 1. Neutron absorption cross section - ^{157}Gd [3]

2.2 Placement in the core

Burnable absorbers can be placed in the core in two ways. The first is the Integral Burnable Absorber (IBA), where the absorber is directly part of the fuel assembly. The IBA subtype is the so-called Integral Fuel Burnable Absorber (IFBA), which has been used by Westinghouse since 1987. This is a thin layer (0.02 mm) of the ZrB_2 absorber sputtered directly onto the fuel pellets. The second method is the Burnable Poison Rod Assembly (BPRA), which is the absorber rod located in guide tubes for regulatory clusters. The disadvantage of the IBA is that absorber is an inseparable part of the fuel assembly. BPRA, on the other hand, carries two negatives associated with more radioactive waste and at the same time influencing the flow of the coolant/moderator when the absorber bars occupy a place where the medium would normally flow. Whilst both ways can be used for pressurized water reactors, only IBAs are used for boiling water reactors. [4] [5]

Material for the production of absorbers varies depending on the manufacturer. American

Westinghouse uses boron as the main element, either as the above-mentioned ZrB_2 or the Al_2O_3-B_4C for the IBA. Another US company, Combustion Engineering, now part of Westinghouse, used both Gd_2O_3 and Er_2O_3, while French Areva uses exclusively Gd_2O_3 for IBA absorbers. [5]

2.3 Advantages and disadvantages

The use of gadolinium in the case of IBA results in a deterioration of the thermal conductivity of the fuel and at the same time a decrease in the melting point, which must be considered in the safety calculations. These problems motivated the development of other variants of erbium and boron-based absorbers. For example, by sputtering the ZrB_2 layer directly onto the fuel, we avoid the negative effects on the material properties of the fuel. IFBA absorbers also have the advantage that their burning can be more precisely designed to reduce residual neutron absorption. Among the disadvantages of an IFBA type absorber can be included, for example, their more complex production, the hygroscopic character of ZrB_2 or the potential increase in moderator temperature coefficient due to higher boron concentration. Thanks to the presence of boron, tritium is also produced, but it does not pose any significant complications in the processing of radioactive waste compared to equivalent gadolinium absorbers. The burning of the boron also produces helium, which leads to the need to reduce the initial pressure of the fuel rod and potentially could affect the pellet-cladding interaction. In general, IFBA absorbers affect the zone less adversely than other types of absorbers due to the thinner applied layer of absorbent material. With higher enrichment of ^{10}B isotope, the ratio of fuel rods with IFBA can be reduced to roughly 12 – 30 %, in the fuel assembly. [4] [5]

The erbium-based absorbers have the advantage over ZrB_2. Due to their effective cross-section behavior, the moderator temperature coefficient is not so much affected. Otherwise, erbium retains positive boron-like properties, so there is no neutron spectrum hardening or larger neutron flux fluctuations, as in Gadolinium. The main disadvantage of the erbium is the relatively high residual absorption caused by its slow burning. [4] [5]The use of dysprosium-based absorbers has been tested on reactors in Belgium prior to the introduction of gadolinium, and it has been shown that dysprosium has very similar properties to gadolinium or erbium in terms of production and operation. [4]

3. EPR reactor

The EPR is a large advanced pressurized water reactor. Total electric power of EPR is 1600 MW, with rated thermal power 4590 MW. The shortcut EPR stands for Evolutionary Power Reactor. EPR was designed on experience with the operation of former N4 and KONVOI reactors in France and Germany. The basic concept of this reactor is a 4-loop pressurized water reactor. This design along with AP1000 and MIR 1200 is one of the first III+ generation reactor. So, it has all the features of generation III+ reactors, such as double containment, core catcher, hydrogen recombiners etc. [6]

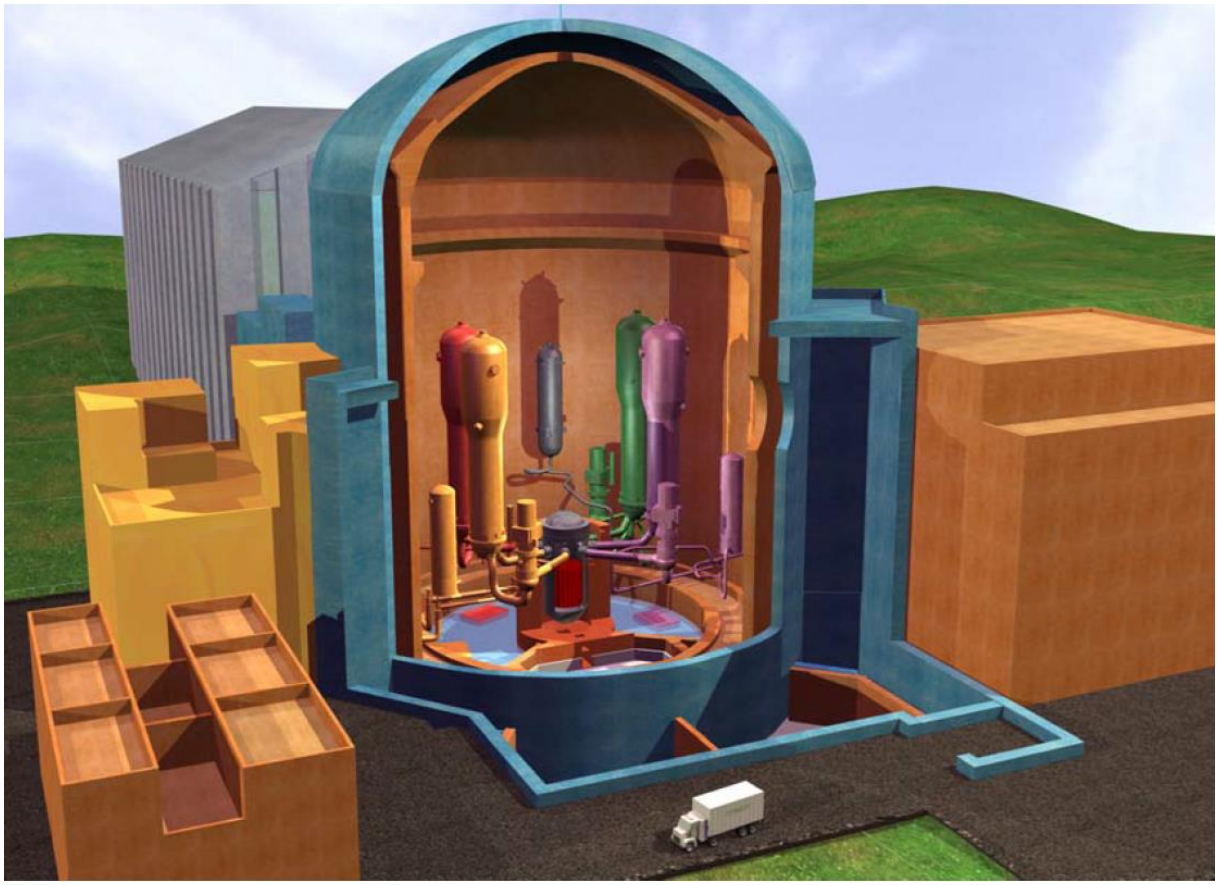


Figure 1. EPR reactor [6]

3.1 Reactor core design

The reactor core is where the fuel is contained and where the fission reaction occurs, thus where the energy produces. A specified number of fuel assemblies are contained in the reactor core. Every fuel assembly consists of fuel rods that are held in bundles by spacer grids and top and bottom fittings. Fuel rods consist of uranium oxide or MOX fuel pellets, EPR

reactor can use up to 100 % MOX fuel. As cladding, it uses M5^{TM} zirconium alloy tube, with M5^{TM} end plugs that are welded at each end. The fuel rods are pressurized with helium. The fuel pellets contain either just fuel, uranium dioxide (UO_2) or the fuel and burnable absorber, uranium dioxide and gadolinia ($UO_2 + Gd_2O_3$). Enrichment can go up to 5 wt% of ^{235}U. The fuel rods are arranged together into 17x17 square grid and form a fuel assembly. Every fuel assembly consists of 265 fuel rods, and total in the reactor, there is 241 fuel assemblies. [6]

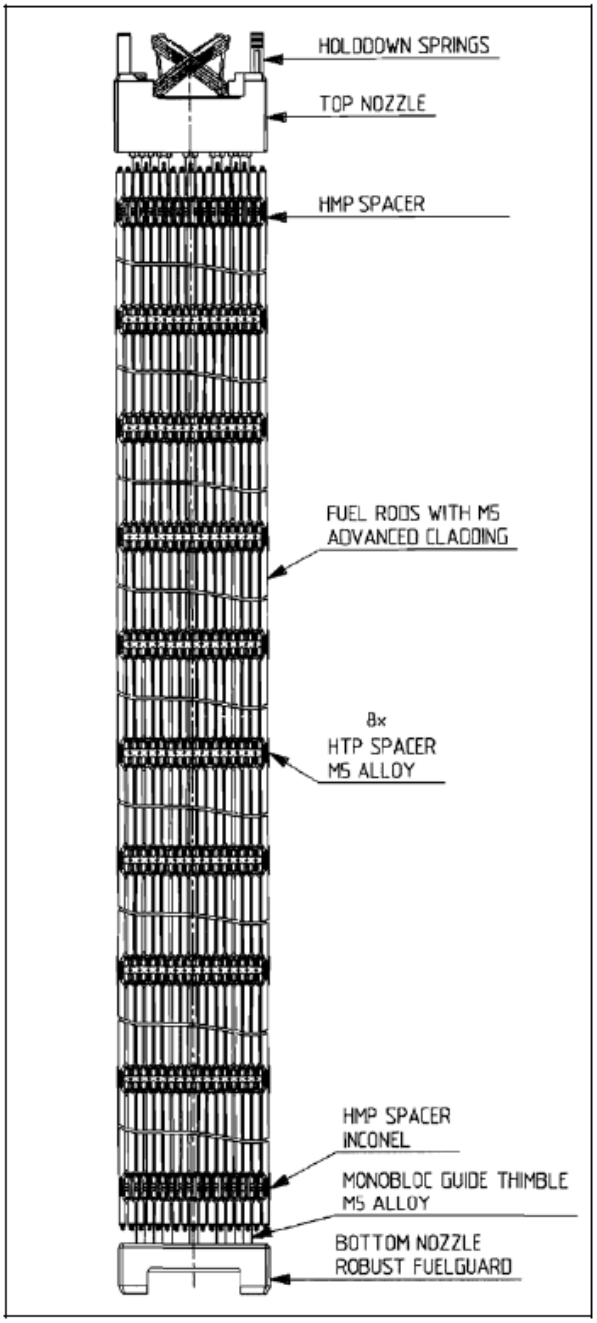
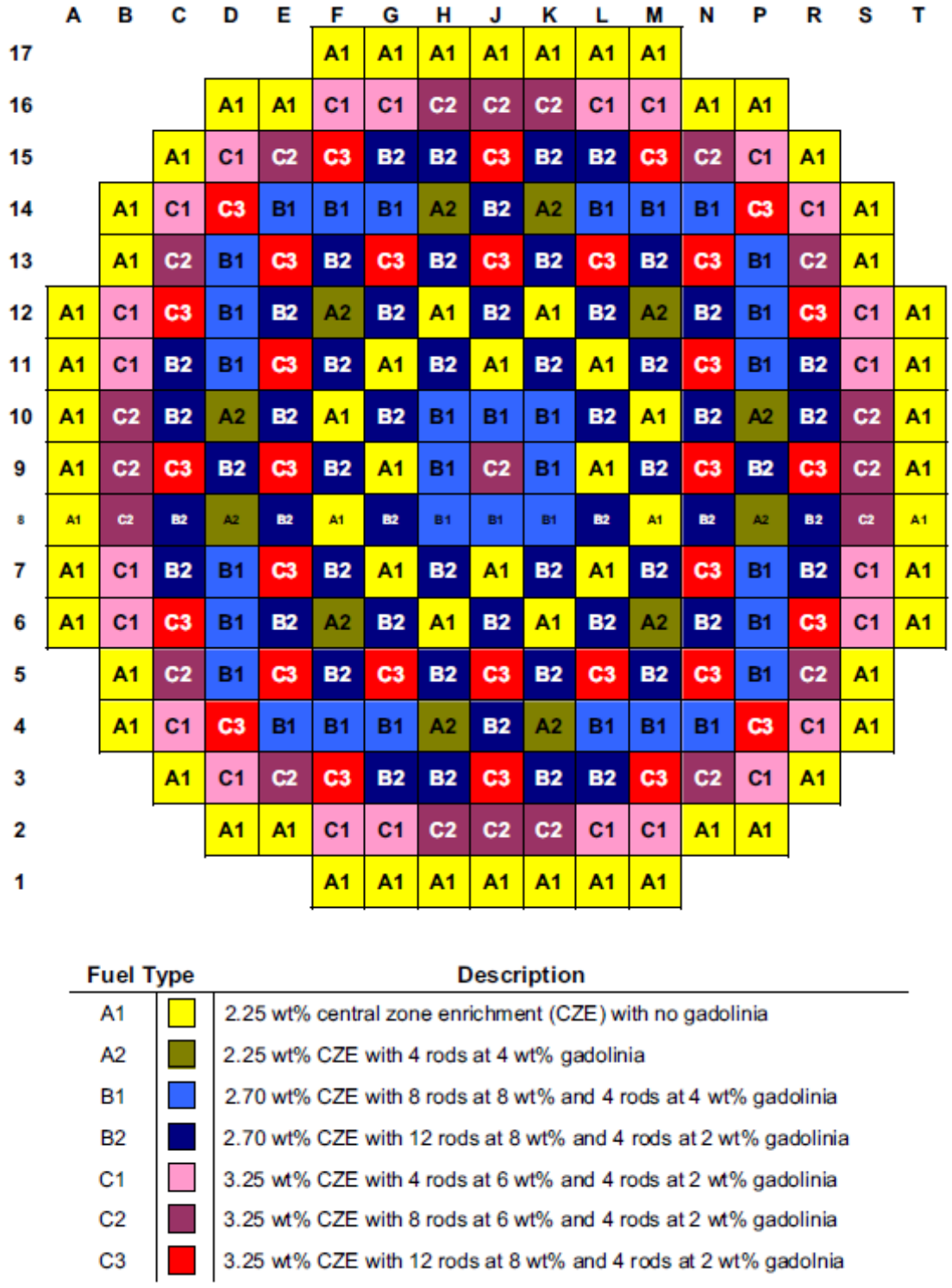


Figure 2. EPR fuel assembly [6]

In the following figure, the typical initial core loading is shown. From this figure, it is clear that EPR uses central zone enrichment from 2,25 wt% to 3,25 wt%. As a burnable absorber is in this case used gadolinia (Gd_2O_3) at a concentration of 2 wt% up to 8 wt%. [6]



Fuel Type	Description
A1	2.25 wt% central zone enrichment (CZE) with no gadolinia
A2	2.25 wt% CZE with 4 rods at 4 wt% gadolinia
B1	2.70 wt% CZE with 8 rods at 8 wt% and 4 rods at 4 wt% gadolinia
B2	2.70 wt% CZE with 12 rods at 8 wt% and 4 rods at 2 wt% gadolinia
C1	3.25 wt% CZE with 4 rods at 6 wt% and 4 rods at 2 wt% gadolinia
C2	3.25 wt% CZE with 8 rods at 6 wt% and 4 rods at 2 wt% gadolinia
C3	3.25 wt% CZE with 12 rods at 8 wt% and 4 rods at 2 wt% gadolnia

Figure 3. Typical initial core loading [6]

3.2 Reactivity control

The EPR is a typical pressurized water reactor, thus it uses rod cluster control assembly (RCCA), soluble neutron poison in the reactor coolant system and burnable absorbers for reactivity control. For short-time changes of reactivity, RCCAs are used. Each RCCA is composed of 24 rods with absorbers that are attached to a spider assembly. These rods are placed in guiding tubes, and RCCAs are in 89 of the 241 fuel assemblies. The absorber rods are made of stainless steel, that contains neutron absorption material, which in this case is material that is composed of 80 wt% Ag, 15 wt% In, and 5 wt% Cd. [6]

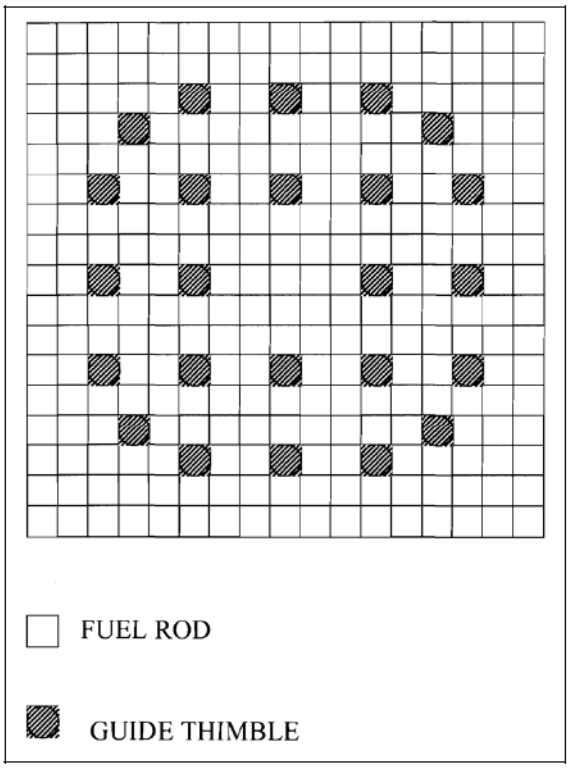


Figure 4. Control rods positioning [6]

As neutron poison in the reactor coolant system, EPR uses soluble boron in the form of H_3BO_3. Soluble neutron poison is used mainly for long-term reactivity control.

As described in chapter 3.1 Reactor core design, as burnable absorber the EPR uses gadolinia in form of Gd_2O_3. Gadolinia is in the reactor placed as Integral Burnable Absorber (IBA), the absorber is directly part of the fuel assembly. In this specific case, the number of burnable absorbers rods is 2 284. The location of the absorber is shown in Figure 3. Typical initial core loading. [6]

4. UWB1 depletion code

Nowadays, modern codes are used to calculate the depletion of nuclear fuel. The depletion calculation is a difficult and complex problem, thus a large computational power and time for calculation are needed.

UWB 1 is a fast depletion code developed at the University of West Bohemia. The main reason for developing this program was to decrease computing time. To decrease the computational time, UWB1 skips the calculation of Boltzmann transport equations in fuel burnup calculation. However, if the UWB1 would skip the calculation of Boltzmann transport equation entirely, the estimate of the neutron multiplication factor would not be accurate enough. That's why it calculates the neutron flux and the effective cross section by implemented Monte Carlo (MC) transport solver at the beginning and at the end of fuel depletion. The rest of depletion time steps are estimated by nuclide-based interpolation scheme of 2 step predictor-corrector (2sPC) depletion scheme. The speed of the MC solver is a result of the focus to minimize the use of CPU at the expense of using RAM. The microscopic cross sections are presumed constant at all time step of the calculation. The MC solver has similar behavior of neutron multiplication factor decrease during depletion as MCNP6, though the UWB1 MC solver is 14 times faster than MCNP6. [7] Burnup solver uses matrix exponential method and Chebyshev Rational Approximation Method (CRAM) for calculation of the next-step inventory of chosen geometric regions. The code is supported by data libraries that are based on ENDF/B-VII.1 nuclear data library, to be as much accurate as it can be.

The UWB1 code enables faster analyses of depletion, thanks to the simplification of the calculation. The EPR model for the UWB1 is made and then based on the calculations, new burnable absorbers for the EPR reactor is designed. [7] [8] [9]

4.1 Calculation phases

UWB1 calculation contains 5 stages – initial, predictor, corrector, depletor and estimator. The scheme of the calculation is shown in Figure 5. Calculation scheme of UWB1. The description of individual phases of calculation according to [8].

The first part of the calculation is called *initial stage*, here the initial state of calculated fuel model by Monte Carlo transport solver is analyzed. The MC solver is based on the principle of random numbers generator. To speed up neutron lifetime, which is calculated in the random walk process, total microscopic cross sections are calculated before the MC simulation. Neutron flux and multiplication factor are then calculated by transport solver in all geometry regions in 4308 energy groups. Next, all the support calculations for burnup solver, the evaluation of fuel basis and relative region powers, takes place. Final estimated formula describes the ratio between production and absorption of neutrons in given nuclear fuel.

In the *predictor* phase, variables from the *initial stage* are applied (primarily cross sections). To the first estimation of fuel model, state at the end of fuel depletion is used, without calling transport solver. Burnup calculation is solved in two loops, inner and outer loop. The inner loop represents the depletion step and the outer loop represent geometry regions. At the end of this phase, final state variables are predicted by the transport solver.

Next step of the calculation is *corrector* phase. This phase works in the same way as *predictor* phase, the only difference is that it uses predicted final state effective cross sections instead of initial state effective cross sections. In this phase, the last stage of transport solver is used. Final average values from *predictor* and *corrector* phase are used for calculation of average state composition of fuel at the end of burnup.

Depletor phase is used to calculate the composition of fuel and the estimate of multiplication factor during burnup. Similarly, to *predictor* phase, burnup calculation is solved in two loops, to which the third loop is added. This third loop is there to predict, correct and average both effective cross sections and fuel composition at the end of depletion step.

The last phase of calculation is *estimator* phase, this phase serves as a comparison of the initial and final value of multiplication factor calculated by transport solver with its estimates.

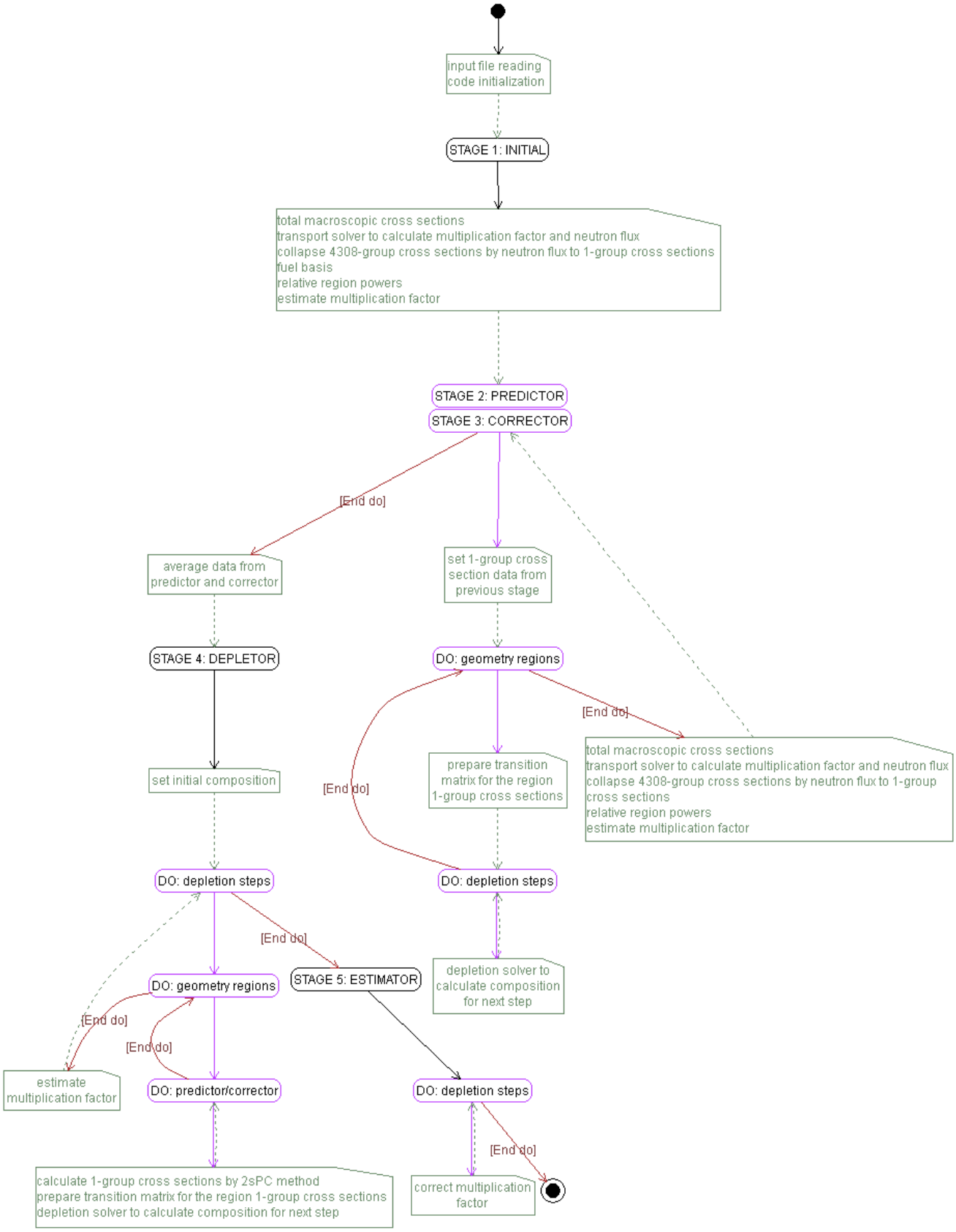


Figure 5. Calculation scheme of UWB1 [8]

4.2 EPR model for UWB1

In UWB1 several reactor models are designed (VVER-1000, CANDU, SFR, etc.) [8] but EPR is not one of them. Thus, EPR model for UWB1 needed to be done. The code allows designing any 2-D geometry described by concentric cylinders in square or triangular lattice. Based on this design, the code is capable of calculating fuel and cladding composition or multiplication factor in any part of the fuel cycle. This calculation is then used for optimization of the burnable absorber. Basic parameters of EPR were found, and they are shown in Table 1. Basic parameters of EPR.

Table 1. Basic parameters of EPR [6]

Fuel geometry	Outer fuel pellet radius R_f [cm]	0.41
	Outer cladding radius R_{cl} [cm]	0.47
	Inner cladding radius r_{cl} [cm]	0.42
	Pitch P [cm]	1.26
Cladding composition	Percentage of Nb [%]	1.00
	Percentage of O [%]	0.13
	Percentage of Hf [%]	0.01
	Percentage of Zr [%]	98.86
Power parameters	Nominal thermal power N_{th} [MW]	4590
	Amount of uranium in 1 fuel assembly m_U [MTU]	0.54
	Number of the fuel assemblies f [-]	241

Once these parameters were known, the EPR model was done. Below the description of the input file is made.

Input file description

The input file can be divided into three parts, in the first part the calculation setup and the fuel geometry is set. In the second part depletion power, time and type are set as well as the libraries. The last part is focusing on nuclear densities.

```
uwb1 EPR depletion test
4                                   prl_threads - number of
threads
40000                               npg - number of neutrons per
generation
5                                   nsng - number of skipped
neutron generations
105                                 tnng - total number of
neutron generations
2                                   n_ccregion - number of
concentric cylinder regions
0.41 0.47                           rccregion - concentric
cylinder region radii
0.6299                              hpitch - half pitch
1                                   lat - lattice type (1=square,
2=hexagonal)
```

Input deck 1. UWB 1 input file part 1

In the input deck above the first part is shown. Here the number of CPU threads are set, the number of neutrons per generation, which is set to 40 000 because of the low statistical error, number of skipped neutron generations, this part is used for testing of the code, and total number of neutron generations, which is roughly from 100 to 120. The other values describe the geometry of the fuel. [8]

EPR uses the square type lattice, the specific fuel geometry values are shown in Table 1. Basic parameters of EPR.

```
43                                    idepl - number of depletion
intervals
3.60000E+01 3.60000E+01 3.60000E+01 3.60000E+01 3.60000E+01
3.60000E+01 3.60000E+01 3.60000E+01 3.60000E+01 3.60000E+01
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power
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1.00000E+01 1.50000E+01 2.00000E+01 2.50000E+01 3.75000E+01
5.00000E+01 6.25000E+01 7.50000E+01 8.75000E+01 1.00000E+02
1.12500E+02 1.25000E+02 1.37500E+02 1.50000E+02 1.62500E+02
1.75000E+02 1.87500E+02 2.00000E+02 2.12500E+02 2.25000E+02
2.37500E+02 2.50000E+02 3.12500E+02 3.75000E+02 4.37500E+02
5.00000E+02 5.62500E+02 6.25000E+02 6.87500E+02 7.50000E+02
8.12500E+02 8.75000E+02 9.37500E+02 1.00000E+03 1.06250E+03
1.12500E+03 1.18750E+03 1.25000E+03  depl_time - irradiation days
1 0 0                                depl_type - regions depletion
(0=no depletion, 1=power depletion, 2=flux depletion)
1 2 2                                reg_libtype - regions
transport/burnup libraries position
900.0 600.0 500.0                    maxwell_kelvin - regions
maxwell temperatures
```

Input deck 2. UWB1 input file part 2

On the Input deck 2, the depletion part of the input file is shown. Calculation of depletion power needed to be done. The calculation was made with the values of thermal power, a number of fuel assemblies and the weight of uranium in one fuel assembly according to the depletion power formula. From this calculation, the depletion power 36 MW/MTU was obtained. Again, the specific values are shown in Table 1. Basic parameters of EPR. Next, the depletion time was set. In this case, it was 1 250 days. This value roughly corresponds with the burnup of 45 000 MWd/MTU, which is the typical burnup for PWR reactors. [8]

$$DP = \frac{N_{th}}{m_u . f} \left[\frac{MW}{MTU}\right] \tag{4.2.1}$$

N_{th} [MW] is a thermal power, m_u $[MTU]$ is a weight of uranium in one fuel assembly and f $[-]$ is a total number of fuel assemblies

```
"/home/michal/Plocha/JP/uwb1/uwb1libs/"         folder with uwb1
libraries
uwb1zaid0423to3820.txt              position of transport
nuclides in depletion nuclides
uwb1nmass.txt                       nuclide mass relative to
neutron
uwb1qvalues4mc.txt                  qvalues for inelastic
reactions
uwb1chi16.txt                       xs_n2n chi data library
uwb1chi17.txt                       xs_n3n chi data library
uwb1chi18.txt                       xs_fission chi data library
uwb1chi91.txt                       xs_inelastic_continuum chi
data library
uwb1nubar.txt                       nubar data library
uwb1angular02.txt                   xs_elastic angular
distribution data library
uwb1angular51t90.txt                xs_inelastic_discrete angular
distribution data library
uwb1angular91.txt                   xs_inelastic_continuum
angular distribution data library
uwb1egrid.txt                       energy grid for xs data
uwb1xscom0900k.txt                  xs data library no1
uwb1xscom0600k.txt                  xs data library no2
uwb1aiiuni.txt                      transition matrix Aii,
universal flux-independent part
uwb1fijphi.txt                      transition data   Fij, part
of Aij, case-flux-dependent part
uwb1aijuni.txt                      transition matrix Aij,
universal flux-independent part
uwb1deplxscom0900k.txt              cross section library for
depletion reactions no1
uwb1deplxscom0600k.txt              cross section library for
depletion reactions no2
uwb1qvalues4depl.txt                recoverable energy library
for depletion reactions
```

Input deck 3. UWB1 input file part 3

Next in the input file that is shown above are the needed data libraries. Data libraries are based on ENDF/B-VII.1 library and contain nuclear data, such as nuclide's properties, cross sections, and radioactive decay description. The uwb1zaid0423to3820.txt library contains the information about each individual nuclide. "*Burnup solver handles 3820 nuclides from radioactive data library, transport solver handles 423 nuclides from neutron data library.*" [8]

```
6                                       number of nuclides in region
1 (fuel)
14                                      number of nuclides in region
2 (clad)
4                                       number of nuclides in region
3 (mod)
   10      41     50100  2.86736E-04   nuclear densities in region
1 (fuel)
   11      42     50110  1.16143E-03
   15      86     80160  4.61843E-02
   16      87     80170  1.75919E-05
  362    3514    922350  1.17142E-03
  365    3518    922380  2.19758E-02
  15      86     80160  3.19823E-04   nuclear densities in region
2 (clad)
  16      87     80170  1.17645E-07
  117   1039    400900  2.23160E-02
  118   1041    400910  4.81299E-03
  119   1042    400920  7.27675E-03
  121   1044    400940  7.21719E-03
  123   1046    400960  1.13845E-03
  124   1081    410930  4.24568E-04
  304   2594    721740  3.62838E-09
  305   2596    721760  1.17926E-07
  306   2597    721770  4.14640E-07
  307   2600    721780  6.04720E-07
  308   2603    721790  3.00226E-07
  309   2606    721800  7.68968E-07
    1      1     10010  5.01551E-02   nuclear densities in region
3 (mod)
   10     41     50100  4.98826E-06
   11     42     50110  2.00784E-05
   15     86     80160  2.50775E-02
eof
```

Input deck 4. UWB1 input file part4

The last part of the input file is the part where the composition of each region is set. First, the number of nuclides in each region is selected. Then the nuclear densities in each region are set. This part contains four columns. The first column is the position of the nuclide in the 423 nuclides library, the second column is the position in the total 3 820 elements library. The third number is ZAID, which is calculated according to the (4.2.2) ZAID equation. [8]

$$ZAID = 10\,000 \cdot Z + 10 \cdot A + m \qquad (4.2.2)$$

For example: ^{238}U $(\mathrm{Z} = 92, \mathrm{A} = 238, \mathrm{m} = 0), \mathrm{ZAID} = 922380.$

And final the last number is the nuclear density N_i $[at/bcm]$ of each individual nuclide in the volume $V = 1 \cdot 10^{24}\ cm^3$. This density is calculated by following equation [8]:

$$N_i = \frac{\rho \cdot w_{f,i} \cdot N_A}{A_{w,i}} \tag{4.2.3}$$

where ρ $[g/cm^3]$ is a mass density of the material, $w_{f,i}$ is a weight fraction of i-th nuclide, $N_A = 0.602214199$ $[at/mol \cdot cm^2/b]$ is an Avogadro number and $A_{w,i}$ $[g/mol]$ is an atomic weight of i-th nuclide. [8]

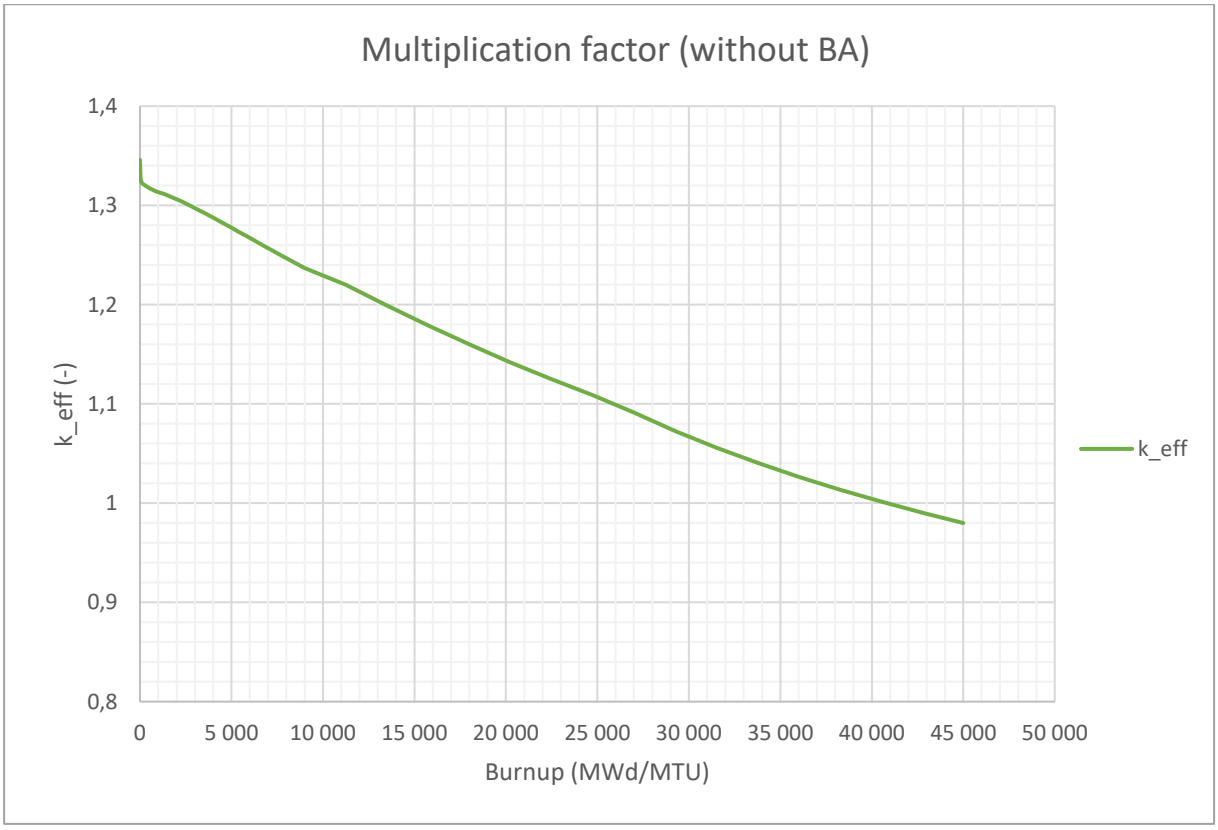
5. Calculation without burnable absorber

Once the UWB1 model of EPR was done, the calculation started. First, it was necessary to make the benchmark calculation without the burnable absorber. This calculation was made for comparison of excess reactivity compensation of each BA. For this calculation, the enrichment was set to 5 wt% of ^{235}U as well as for the other calculations.

In the Graph 2 below the behavior of multiplication factor during burnup can be seen. From this calculation, the result of initial multiplication factor was obtained $k_{eff} = 1.346$, afterwards the reactivity $\rho = 0.258$ was calculated by:

$$\rho = \frac{k_{eff}-1}{k_{eff}} \; [-] \; [10] \qquad (5.1.1)$$

Another thing that can be seen from this graph is at which burnup the curve crosses $k_{eff} = 1$ line, in this case it is for burnup $B = 40\,827\ MWd/MTU$.



Graph 2. Multiplication factor without BA

6. Single element burnable absorber

This part of the thesis describes the calculation of a single element burnable absorber. The first thing that was made here was the selection of suitable elements. Then the initial step calculation was made and at the end, the detailed calculations of 6 most appropriate elements were made.

6.1 Element selection

As mentioned above the first thing that was necessary for the further process, was the element selection. The ideal element for burnable absorber is element with large absorption cross section σ_a. Also, it needs to have daughter nuclide with lower absorption cross section than the mother nuclide in order to be burnable. The large absorption cross section of mother nuclide causes neutron to be absorbed, thus decreasing the multiplication factor.

The criterion for element selection was, as described before, the capture cross section. With this criterion, 11 elements were chosen as the appropriate for the burnable absorber. Those elements can be seen below.

Table 2. Elements suitable for burnable absorber

Element	Nuclide with largest σ_c	Neutron capture cross section σ_c $[b]$	Nuclide abundance [%]
Cd	^{113}Cd	20 615	12.23
Gd	^{157}Gd	254 000	15.65
B	^{10}B	3 846	20.00
Eu	^{151}Eu	9 190	47.80
Er	^{167}Er	649	22.87
Hf	^{177}Hf	375	18.60
Sm	^{149}Sm	40 140	13.82
Dy	^{164}Dy	2 982	28.26
Ir	^{192}Ir	954	37.3
Lu	^{176}Lu	2 020	16.94
Hg	^{199}Hg	2 150	2.60

6.2 Initial step calculation

The initial step calculation was executed for the burnup $\boldsymbol{B = 0\ MWd/MTU}$. The reason why this calculation was made is simple. Due to this calculation, the initial drop of multiplication factor for each individual element was obtained. The calculation was performed for **concentration** of each element of **0.0125 %** in the fuel, this value was selected based on the consultation with my consultant. Also in the calculation is assumed natural element without any enrichment. After analyzing this data six elements were selected for further examination. In the table below, the multiplication factor decrease, reactivity and the reactivity difference compared to the state without the BA can be seen. The multiplication factor and reactivity for the state without BA are $\boldsymbol{k_{eff} = 1.346, \rho = 0.258}$.

Table 3. Initial step calculation results

Element	Multiplication factor k_{eff} $[-]$	Reactivity ρ $[-]$	Reactivity difference $\Delta\rho$ $[pcm]$
Cd	1.301	0.231	2709
Gd	1.222	0.182	7640
B	1.278	0.217	4123
Eu	1.318	0.241	1703
Er	1.343	0.256	271
Hf	1.343	0.255	309
Sm	1.278	0.218	4080
Dy	1.338	0.253	554
Ir	1.341	0.254	404
Lu	1.345	0.256	193
Hg	1.347	0.257	88

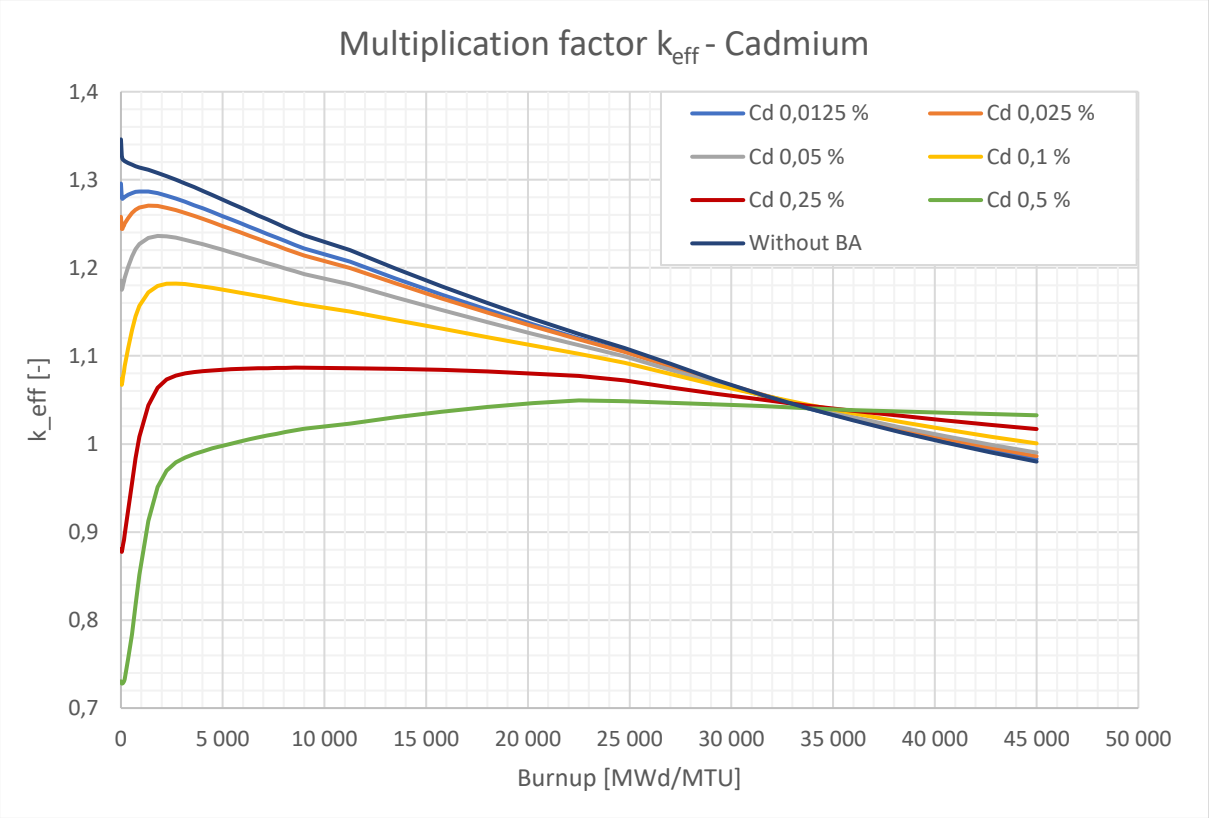
The green highlighted ones are set for further examination, specifically Cadmium, Gadolinium, Boron, Samarium, Dysprosium, and Iridium.

6.3 Detailed calculation of six chosen elements

As the next step, the detailed calculation of each element was done. By detailed calculation, it is meant the calculation for the whole fuel cycle. In this case, the final burnup is $B = 45\,000\ MWd/MTU$. The calculation is made for the EPR model that is described in EPR model for UWB1. The enrichment of ^{235}U is 5 %, the cladding is M5^{TM} cladding and as the moderator light water with 600 ppm of boron is used. Detailed parameters of EPR can be found in the Table 1. Basic parameters of EPR.

Cadmium

Cadmium is an element that already found its purpose in the nuclear field. It is used as an absorbent element in control rods, the EPR is using cadmium as one of the elements in control rods. Six concentrations of cadmium in the fuel was selected for the calculation, specifically 0.0125 wt%, 0.025 wt%, 0.05 wt%, 0.1 wt%, 0.25 wt%, and 0.5 wt%. In the chart below the behavior of multiplication factor for individual concentration is shown. [6]

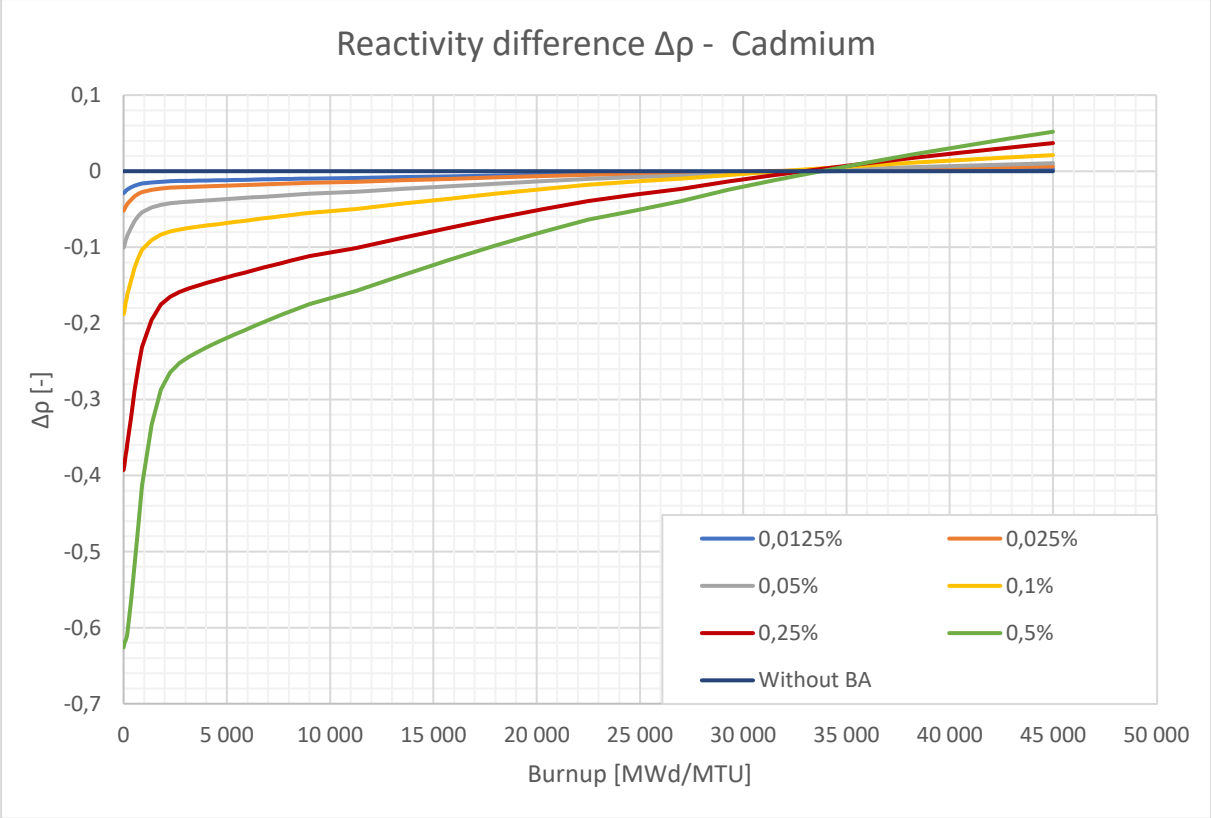


Graph 3. Multiplication factor - Cadmium

From the Graph 3 it is evident that at the beginning there is a drop of the multiplication factor, then increase till it reaches a certain level and then it starts to decrease. The drop at the beginning is larger as the concentration of cadmium increases. For the last two concentrations (0.25 wt% and 0.5 wt%) the initial drop of k_{eff} is too big, thus they are unusable. From the shape of individual curves, it is evident that cadmium has large absorption cross section, thus burns up fast. So, cadmium can be labeled as fast burnable absorber.

The following chart describes the reactivity difference of individual concentrations from the state without the burnable absorber. The desirable state is that at the end of the fuel cycle the reactivity curve is as close as possible to the curve without the BA or slightly above it. If the curves are above the "Without BA" curve, it means that positive reactivity is released, thus the prolongation of the fuel cycle is possible. Again, in this chart, the two last concentrations are unusable, due to the large decrease of reactivity at the beginning. The reactivity difference was calculated by:

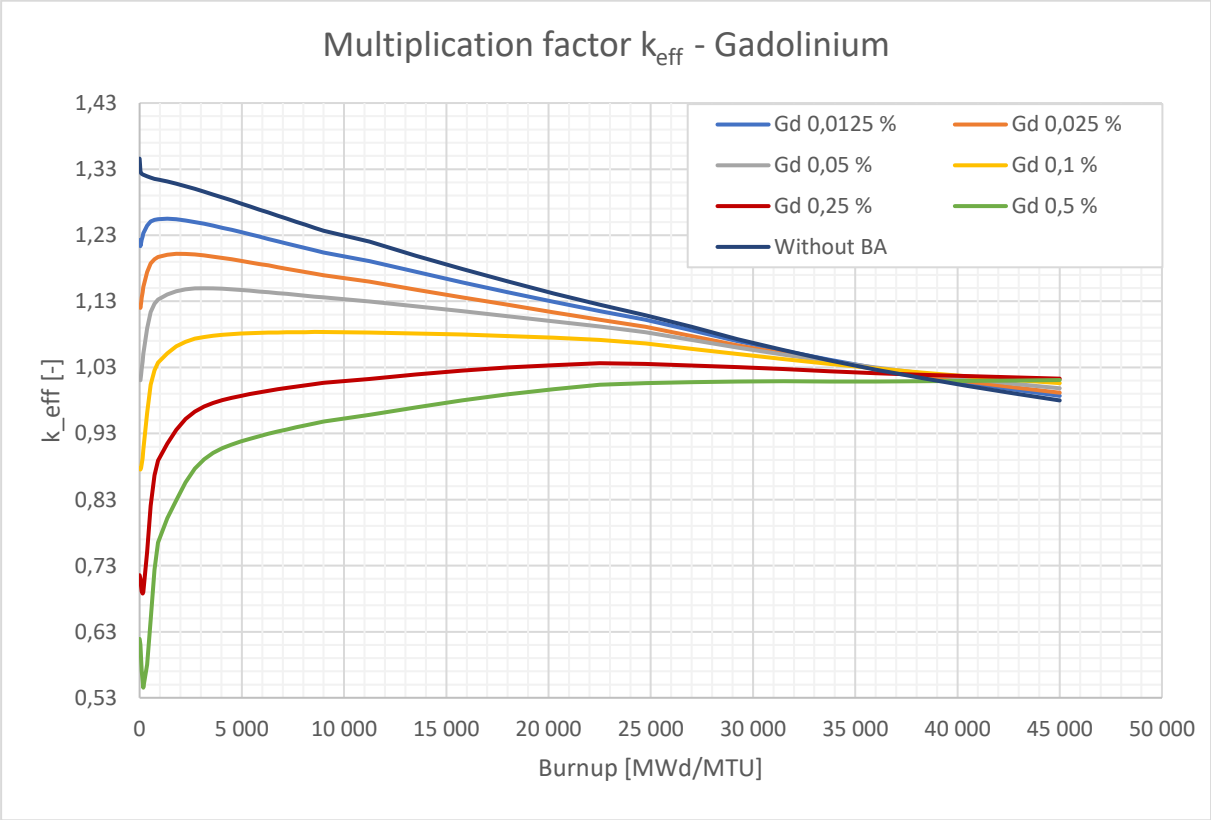
$$\Delta\rho = \left(\frac{k_{eff_{BA}} - 1}{k_{eff_{BA}}}\right) - \left(\frac{k_{eff_{NAT}} - 1}{k_{eff_{NAT}}}\right) \qquad (6.3.1)$$



Graph 4. Reactivity difference - Cadmium

Gadolinium

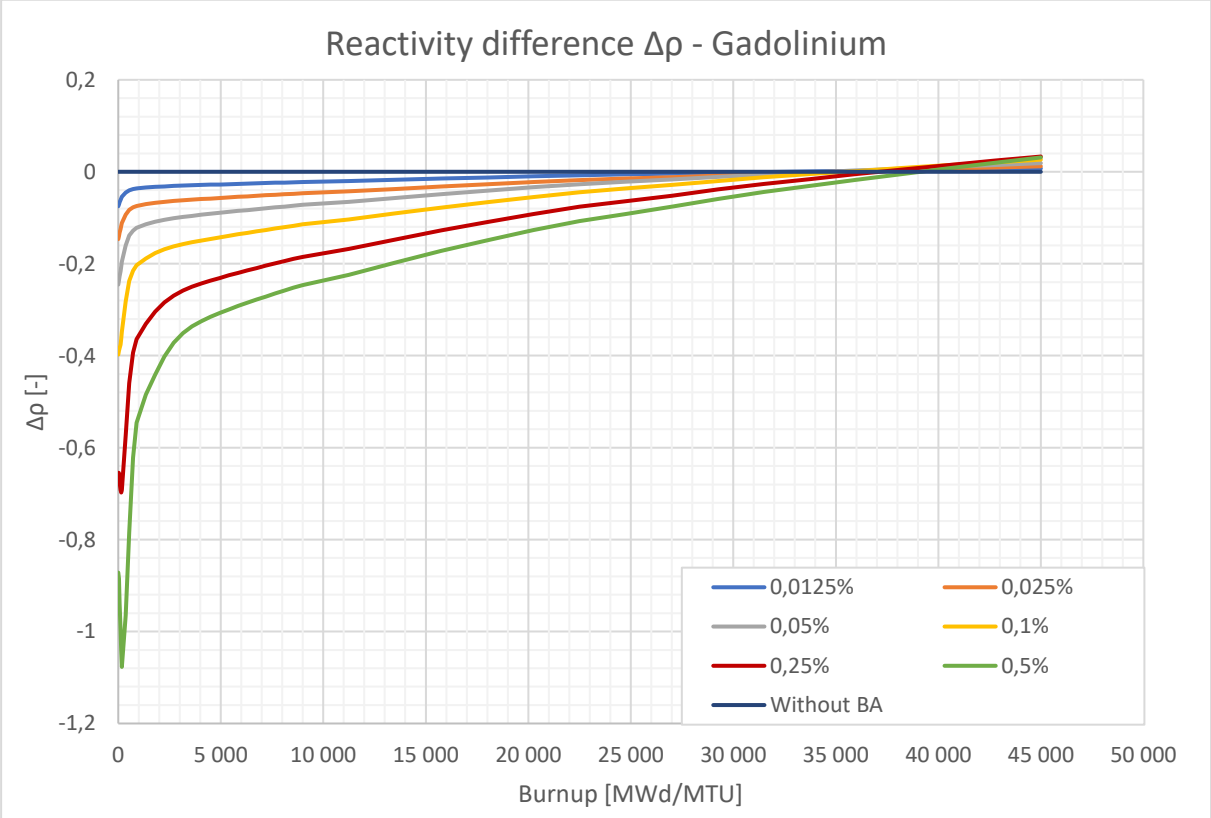
Gadolinium is also an element that is commonly used in nuclear industry. It is used in some PWR and VVER reactors as a burnable absorber in the form of Gd_2O_3. Again, the EPR is using Gd_2O_3 as a burnable absorber as well. Gadolinium has a large neutron capture cross section, specifically, ^{157}Gd has the largest one, followed by ^{155}Gd. The natural abundances of ^{157}Gd and ^{155}Gd are 15.7 % and 14.8 %. The concentrations are set to the same values as in the previous case. The behavior of multiplication factor can be seen in the Graph 5. [2] [6]



Graph 5. Multiplication factor - Gadolinium

From behavior that is shown in Graph 5, it is clear, that at the beginning there is a similar drop of multiplication factor as in the case of cadmium. The peak in gadolinium is not that obvious as in cadmium. After the peak, the curve starts to decrease again. Like the case of cadmium, the last two concentrations are unusable, due to the very large multiplication factor drop at the beginning. The difference from cadmium is, that in the case of gadolinium, even the concentration 0.1 % is unusable, due to the same reason. This is caused because of the enormous neutron absorption cross section of gadolinium.

Below (Graph 6) the reactivity difference for gadolinium can be seen. From the shape of the curves, gadolinium can be labeled as fast BA. At the beginning, large compensation of reactivity is seen. This chart supports the statement that the last three concentrations are inappropriate, the compensation of reactivity is too large here. Other three concentrations look good, all of them are close to the curve "Without BA" at the end and some of them are even above. As described in the cadmium part that is desirable.

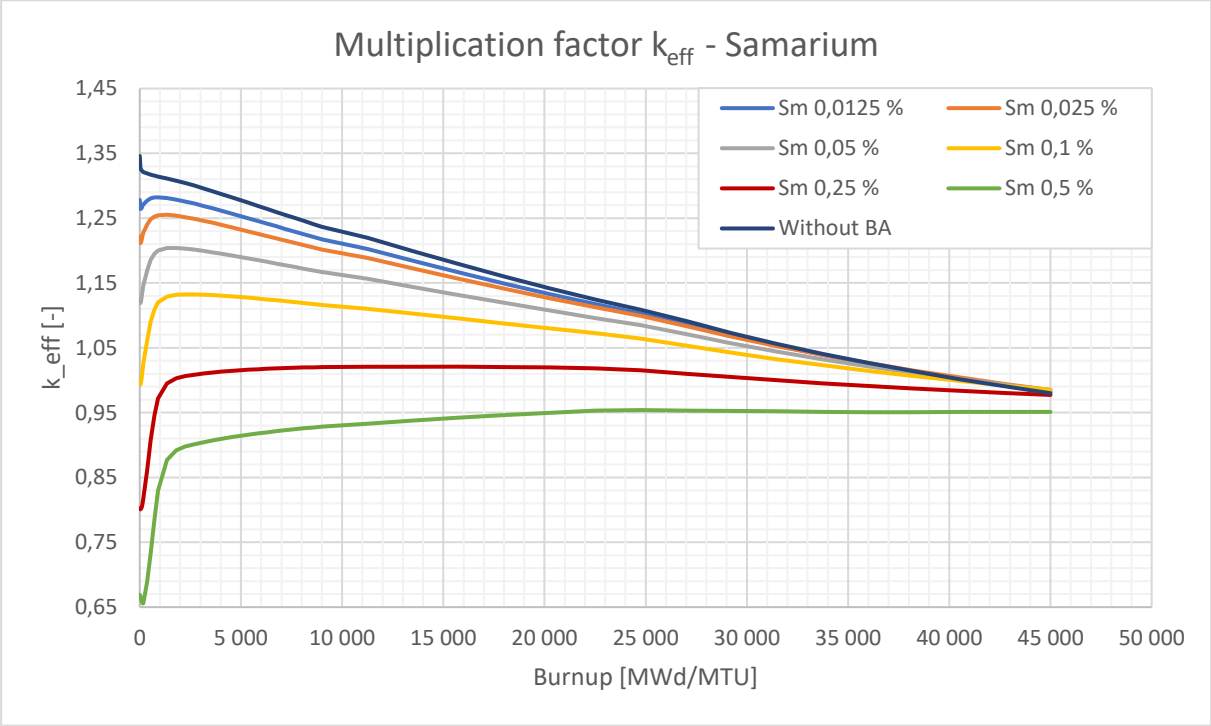


Graph 6. Reactivity difference - Gadolinium

Samarium

Samarium is an element that is also known to the nuclear engineers. Mostly it is because of the samarium poisoning of the reactor, a state when the reactor cannot be started due to the large concentrations of Sm, which has a large neutron capture cross section. The largest cross section has the ^{149}Sm ($\sigma_c = 40\ 140\ b$) [3] with the natural abundance of 13.82 %. The big problem about samarium poisoning is that the ^{149}Sm is a stable isotope, thus it not decays. The only way how to get rid of ^{149}Sm is by absorbing a neutron. [1]

The behavior of multiplication factor of Samarium is shown in Graph 7. Again, the concentrations are the same as in the previous cases.

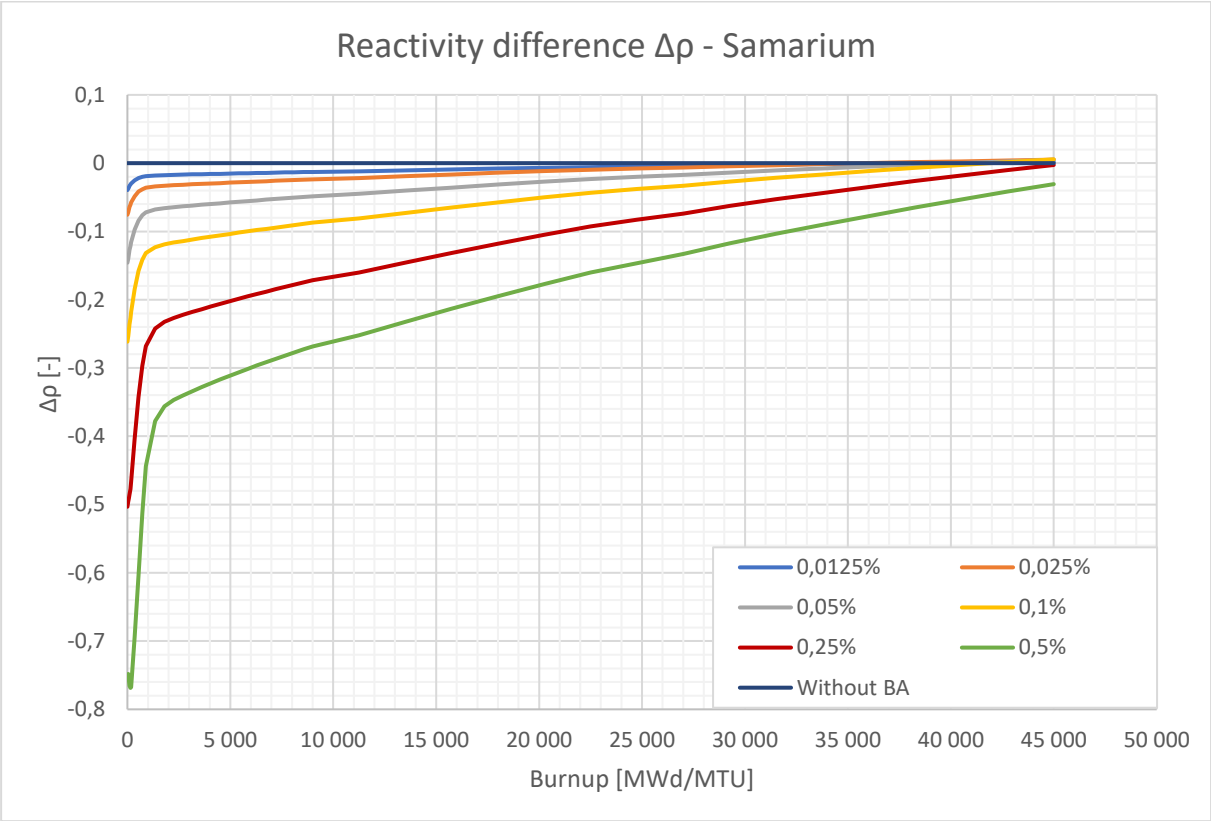


Graph 7. Multiplication factor – Samarium

At the first sight, it is seen, that the samarium is a fast burnable absorber as well as cadmium and gadolinium. In comparison to the gadolinium, the samarium curves copy the "Without BA" curve well and they are closer to it. The initial drop of the multiplication factor is not that big as it is in gadolinium or cadmium case. This means that again the two biggest concentrations are inappropriate but the third biggest concentration is usable. The concentration 0.1 % is at the beginning slightly below the $k_{eff} = 1$, this means that if the concentration of boron acid would be lower, this concentration of BA is good for use. After the initial drop the curve starts to increase again, the peaks in the case of samarium are smaller than in the case of gadolinium and cadmium. At the end of the fuel cycle the samarium curves are slightly above the "Without BA" curve thus a small prolongation of the fuel cycle would be possible. The exception makes the 0.25 % and 0.5 % concentration.

On the next page, the Graph 8. Reactivity difference - Samarium is shown. The two lowest concentration copies the "Without BA" curve very well same as in the multiplication factor. As described in the multiplication factor the concentration 0.1 % would be possible for use, if

the concentration of boron acid would be decreased. At the end of the fuel cycle, almost all the concentrations are close to the "Without BA" line, except for 0.5 %. The first four concentrations are slightly above the zero line, so the positive reactivity is released. This can lead to the prolongation of the fuel cycle.

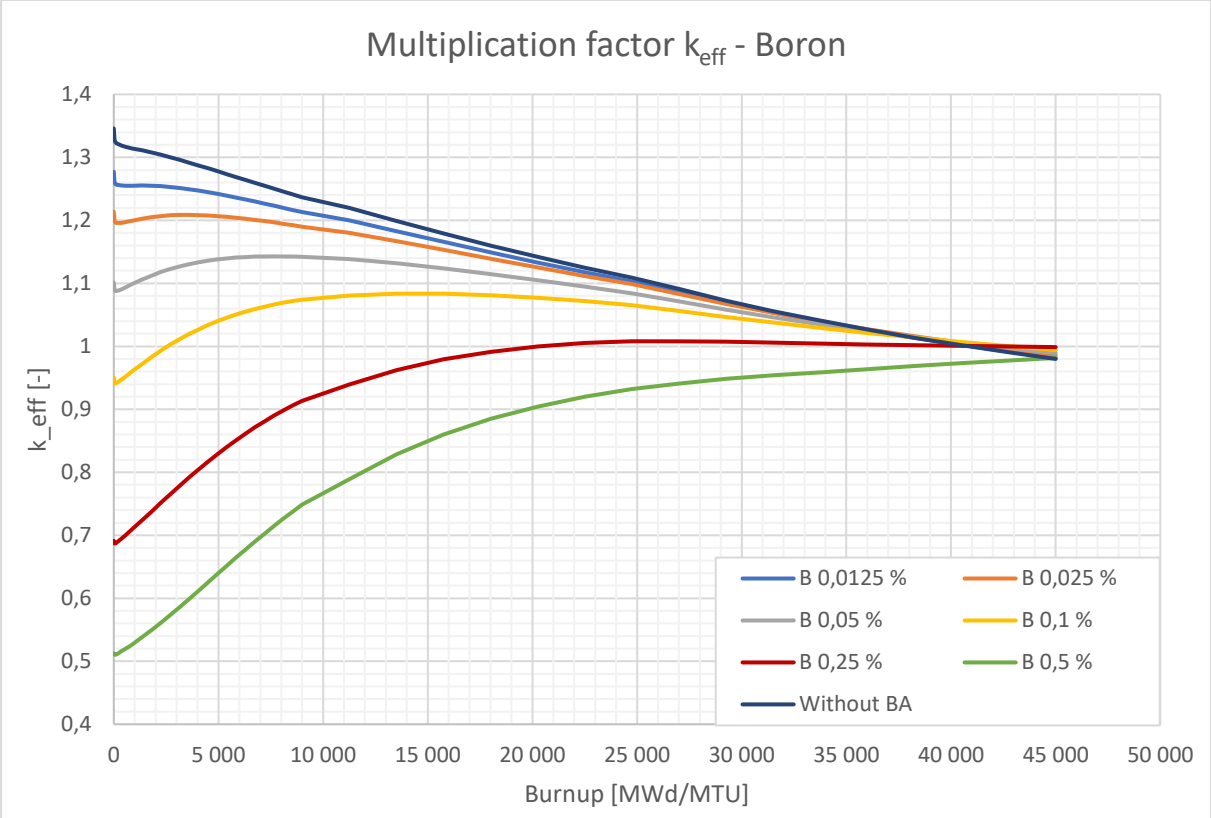


Graph 8. Reactivity difference - Samarium

Boron

Boron is an element heavily used in nuclear industry. The main use of boron is for the reactivity control. Regarding the long-term reactivity control, it is the chemical shim. The chemical shim means boron is used as soluble neutron poison in the reactor coolant system in the form of boric acid (H_3BO_3). The boron is also used for the short-term reactivity control. Many of the control rods used in the reactors use boron as an absorbent material, specifically ^{10}B (i.e. VVER-440, VVER-1000). Boric acid is also used to keep the reactor in the subcritical condition while the maintenance is made. In this case, a high concentration of boric acid is used. As described in the chapter 2.1 Materials for BA, ^{10}B is also used as a burnable absorber in some reactors. Compared to the gadolinium, boron compensates reactivity longer but not so

heavily, due to larger neutron absorption cross section of gadolinium. That is why boron is considered as a slow burnable absorber. [1]

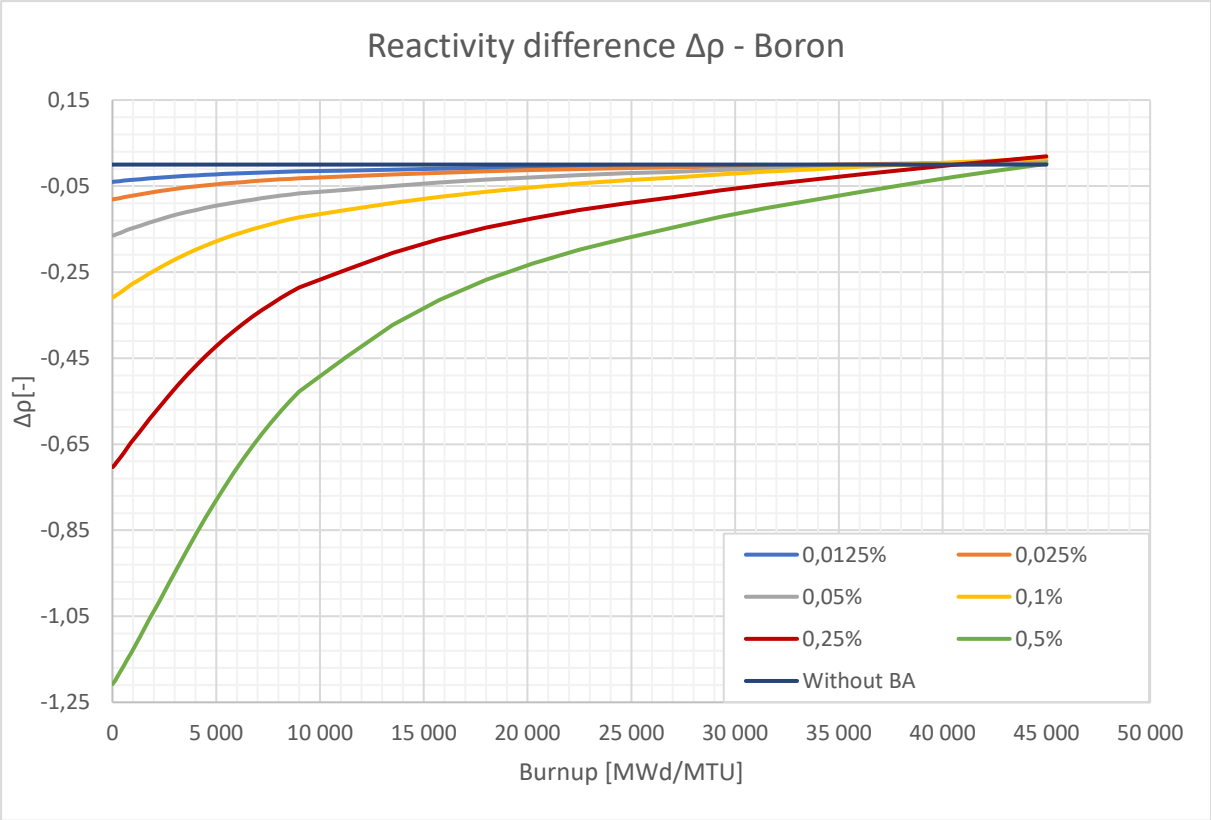


Graph 9. Multiplication factor - Boron

As explained in the previous paragraph boron is considered as a slow burnable absorber. That means it compensates excess reactivity more constantly. This can be seen from the multiplication factor behavior of boron shown in the Graph 9. The curves are more constant, the peak after the initial compensation of reactivity is not that obvious, and for the lowest concentration, there is no peak, just a little sign of it. The initial compensation really depends on concentration, with boron it is more obvious than with other elements. The last three concentrations are not suitable for use as a burnable absorber, especially the concentration of 0.5 % where the initial compensation is very large. At the end it can be seen, that all the concentrations are slightly above the “Without BA” curve, so again the prolongation of the fuel cycle is possible.

The Graph 10 shows the reactivity difference of the boron compared to the state without burnable absorber. From this graph, it is seen, that the curves are more constant. The lower

concentrations are nicely copying the “Without BA” curve. As it was said in the description of the multiplication factor behavior, the concentration 0.5 % brings a large negative reactivity at the beginning. This concentration along with the 0.25 % and 0.1 % is inappropriate to use. At the end of the fuel cycle, the positive reactivity release can be seen, since the curves of individual concentrations are above the curve without the burnable absorber.

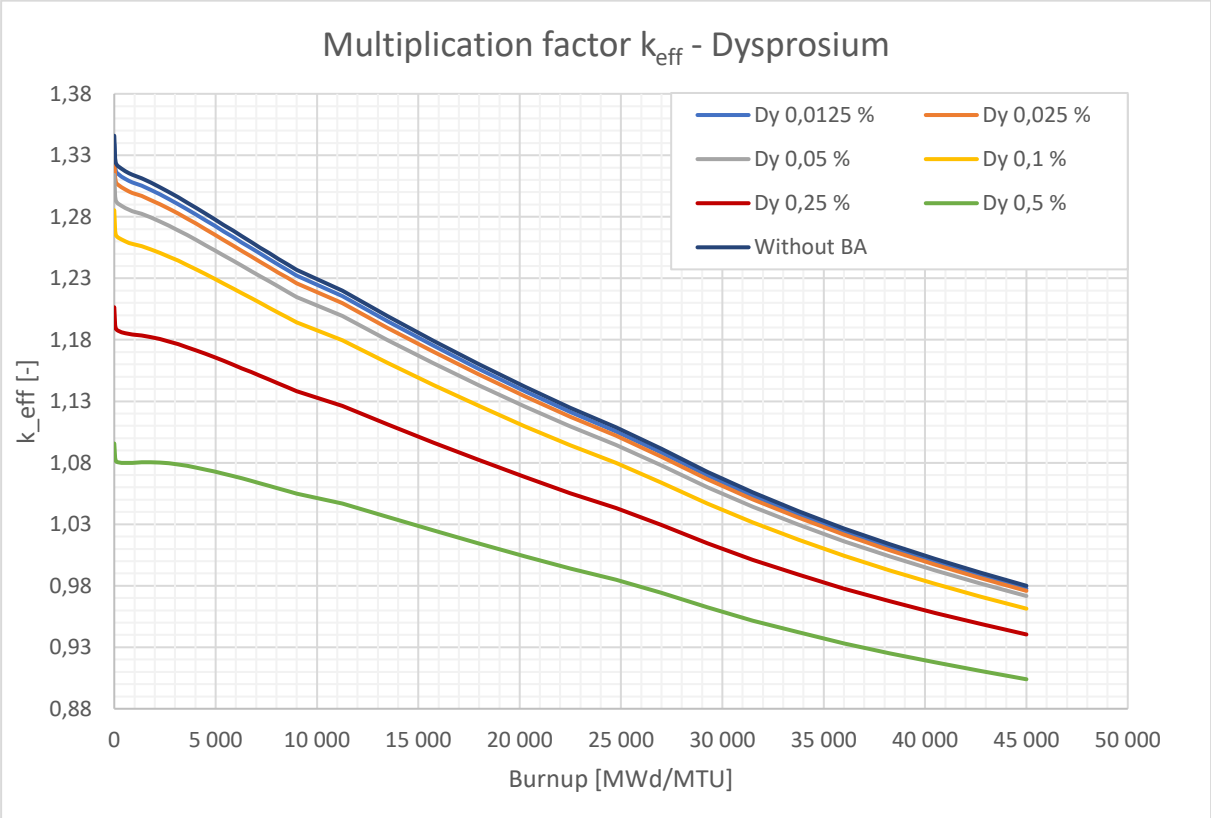


Graph 10. Reactivity difference - Boron

Dysprosium

Dysprosium has been tested as a burnable absorber in Belgium before the gadolinium burnable absorber was introduced. It has similar properties to gadolinium or erbium in the terms of production and operation of the burnable absorber. Today the idea about dysprosium-based burnable absorber is again interesting, due to the future use of dysprosium as BA in the new fuel for ACR reactor. This fuel will be composed of uranium enriched to 2.1 % ^{235}U in the outer elements and 7.5 % of dysprosium in natural UO_2 in the central element. [4] [11]

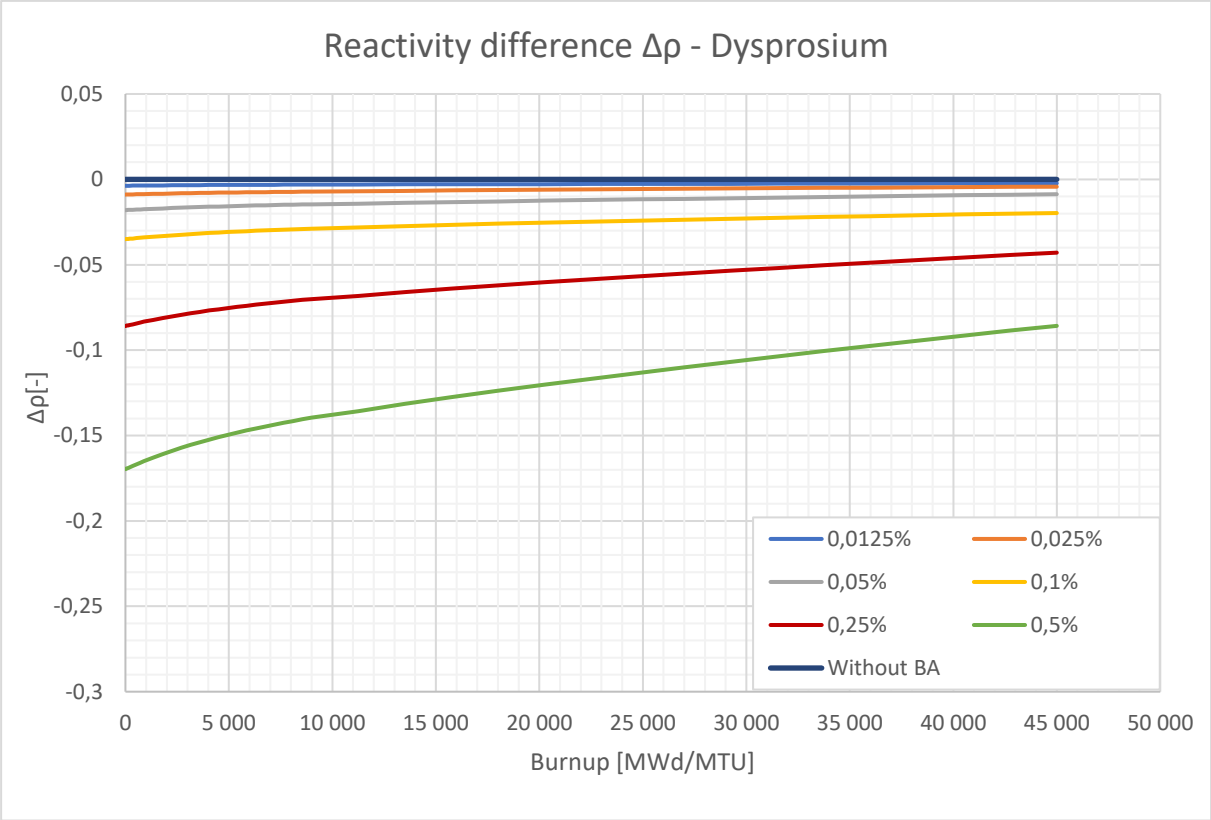
The multiplication factor behavior of dysprosium is shown in Graph 11.



Graph 11. Multiplication factor - Dysprosium

The dysprosium is a typical slow burnable absorber, as it can be seen from the graph. The curves are nicely copying the curve without the burnable absorber, they just move downwards with increasing concentration. The concentrations 0.25 % and 0.5 % can be eliminated again, thus the multiplication factor at the end is too low. It is evident that there are no peaks in here like it was in the previous cases. The multiplication factor constantly decreases, just at the beginning there is a larger drop, but in comparison to the initial drops in the previous cases, it is negligible. Also, there is a change at the end of the fuel cycle in comparison to the previous cases. In the case of dysprosium, there is not any single curve that would be above the curve without burnable absorber. This leads to the fact that by the means of the burnable absorber, there is no way how to prolong the fuel cycle. It can be prolonged by different means such as power coefficient of the reactor. In the Graph 12 is shown the reactivity difference of the dysprosium. Same as the multiplication factor, the reactivity difference is more constant, than the previous cases. All the concentrations are copying the shape of the curve without burnable absorber, but the two largest concentrations are too far away from it, thus they

cannot be used. The problem with this element is that the initial drop of reactivity is rather small. At the end of the fuel cycle, none of the concentrations are above the "Without BA" curve, so there is no release of positive reactivity.

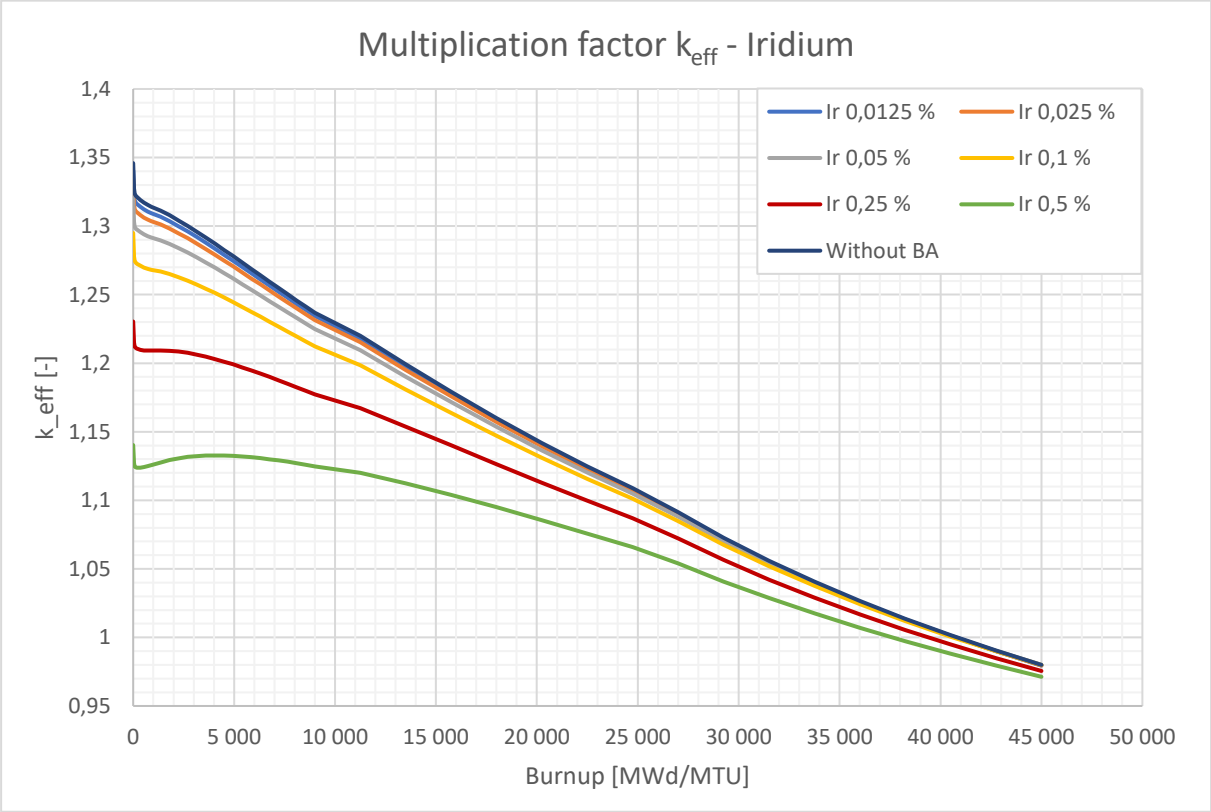


Graph 12. Reactivity difference – Dysprosium

Iridium

Iridium is a very hard though brittle silvery-white metal of the platinum group. It is marked as the second densest element on the planet right behind the osmium with density $\rho = 22.65 \frac{g}{cm^3}$. Iridium is also very rare element, with its abundance of 0.001 ppm in crustal rock is 40 times less abundant than gold. In nature, it occurs in two stable isotopes ^{191}Ir and ^{193}Ir with concentration of 37.3 % and 63.7 %. [12]

The Graph 13 shows the multiplication factor behavior of iridium.

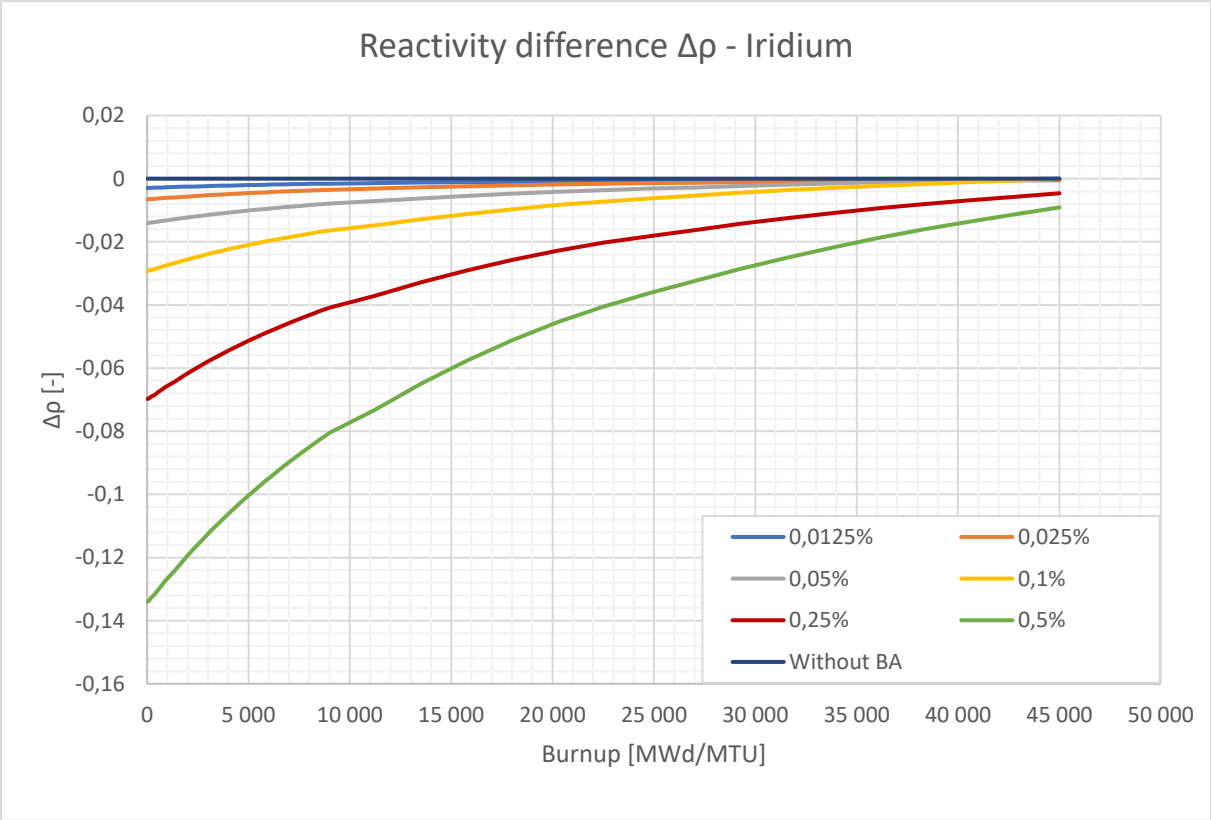


Graph 13. Multiplication factor - Iridium

The multiplication factor behavior of iridium is similar to the dysprosium, even though the initial drop is not that big. The curves are copying the shape of the curve without the burnable absorber and at the end, they are getting closer to it. The concentration 0.05 % is the only one that is slightly above the curve without the BA at the end of the fuel cycle. It cannot be seen from the graph, but from the calculation results, it is evident. Probably with the higher burnup even the other concentrations would be above the "Without BA" curve. In the case of iridium, all the concentration can be used, but the last two concentrations will cross to $k_{eff} = 1$ line at lower burnup. In the case of 0.25 % concentration it is around 39 000 MWd/MTU and for the concentration %.5 % it is roughly 36 500 MWd/MTU.

In the next Graph 14 the reactivity difference for iridium can be seen. As it was said in the previous paragraph, the shape is like the dysprosium, but the initial drop of reactivity is bigger with dysprosium. From the shape of the curves, iridium can be labeled as a slow burnable absorber. At the end of the fuel cycle, the curves are getting closer to the curve

without the burnable absorber. The two largest concentration will probably need larger burnup to get even closer to the "Without BA" line. Like the multiplication factor, here the concentration 0.05 % is the only one that is slightly above the zero-reactivity line, thus a small amount of positive reactivity is released. This causes that the fuel cycle can be prolonged. The other concentrations are below this line and no positive reactivity is released.



Graph 14. Reactivity difference - Iridium

7. Double element burnable absorber

After the results of single element burnable absorber, the calculation of double element burnable absorber began. Double element BA is a burnable absorber that is composed of two elements, ideally one fast BA and one slow BA. The desirable state is that at the beginning of the fuel cycle the drop of reactivity is large, due to the fast burnable absorber. Then the shape of the curve is more constant due to the slow burnable absorber. The division of burnable absorbers needed to be done, it is shown in Table 4.

Table 4. Division of burnable absorbers

Fast burnable absorbers	Slow burnable absorbers
Cadmium	Boron
Gadolinium	Dysprosium
Samarium	Iridium

From the division, it is clear, that there are three fast and three slow burnable absorbers. The calculation was made for a combination of each fast BA with each slow BA, in total 9 combinations. As initial condition for this calculation the multiplication factor $k_{eff} = 1.2$ at burnup $B = 2\,250 \frac{MWd}{MTU}$ was set. The burnup $B = 2\,250 \frac{MWd}{MTU}$ was selected because it is approximately where the peak after the initial drop is.

First, it was necessary to determine the concentration of the single element, which will fulfill the initial condition. Several testing calculations were made, till the approximate concentration that will meet the $k_{eff} = 1.2$ initial condition was known. The next step was to find out the concentrations of double element BA by use of the weight function. The fraction of each element was set from 0 to 1 with a step of 0.2. The example is shown in the Table 5.

Table 5. Example of determining the concentrations of double element BA

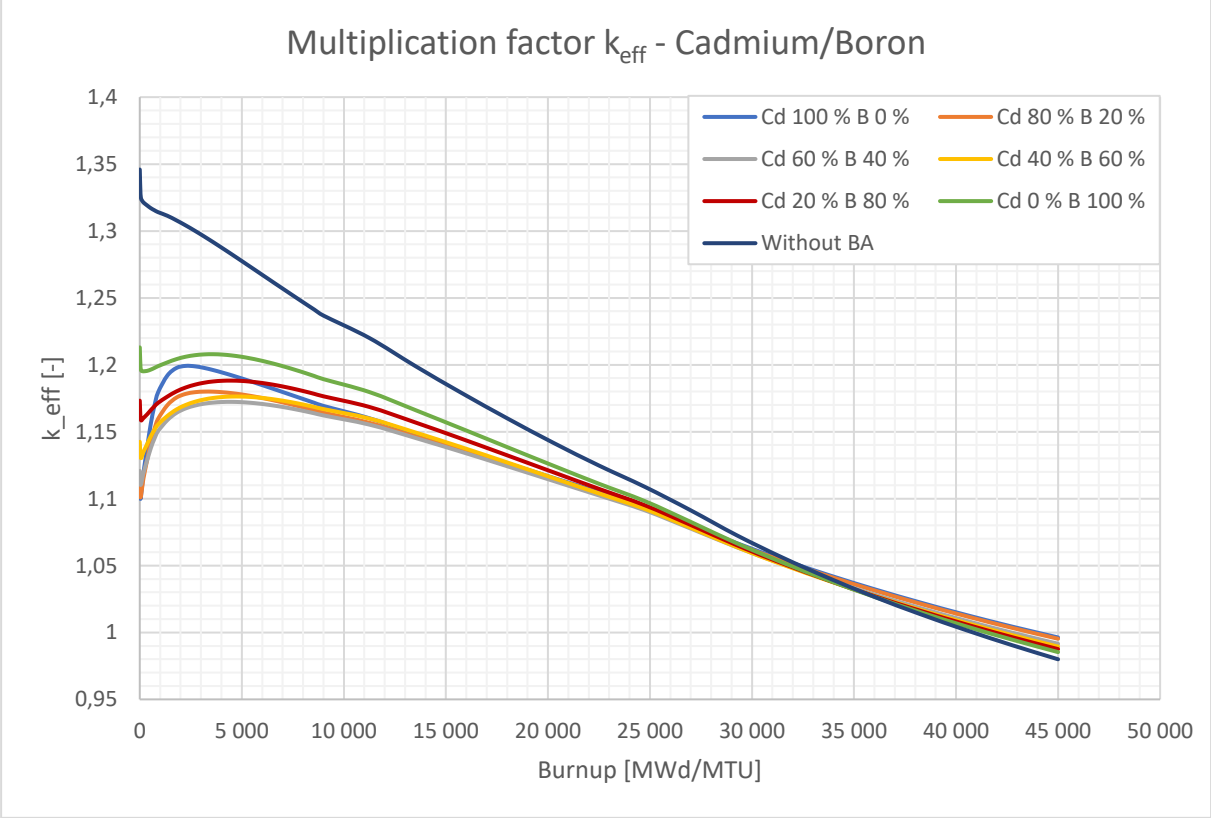
Fraction of each element		Concentration of BA for $k_{eff} = 1.2$ [%wt]		
Gadolinium	**Dysprosium**	**Gadolinium BA**	**Dysprosium BA**	**Gadolinium/Dysprosium BA**
1	0	0.025	0.227	0.0250
0.8	0.2	0.025	0.227	0.0654
0.6	0.4	0.025	0.227	0.1058
0.4	0.6	0.025	0.227	0.1462
0.2	0.8	0.025	0.227	0.1866
0	1	0.025	0.227	0.2270

7.1 Calculation of individual combinations

Since the concentrations for each combination was known, the detailed calculation can be started. Again, the calculation was made for the whole fuel cycle, which means for the burnup $B = 45\,000 \frac{MWd}{MTU}$. The enrichment of uranium was 5 % and as the cladding the alloy M5 was used. The moderator was water with 600 ppm of boric acid.

Cadmium/Boron

In this part, the calculation for a different fraction of each element is made. The fast burnable absorber cadmium is characterized by the large drop of multiplication factor at the beginning. Contrast the slow burnable absorber boron has a nice smooth behavior of multiplication factor. The behavior of multiplication factor for this combination can be found in Graph 15.

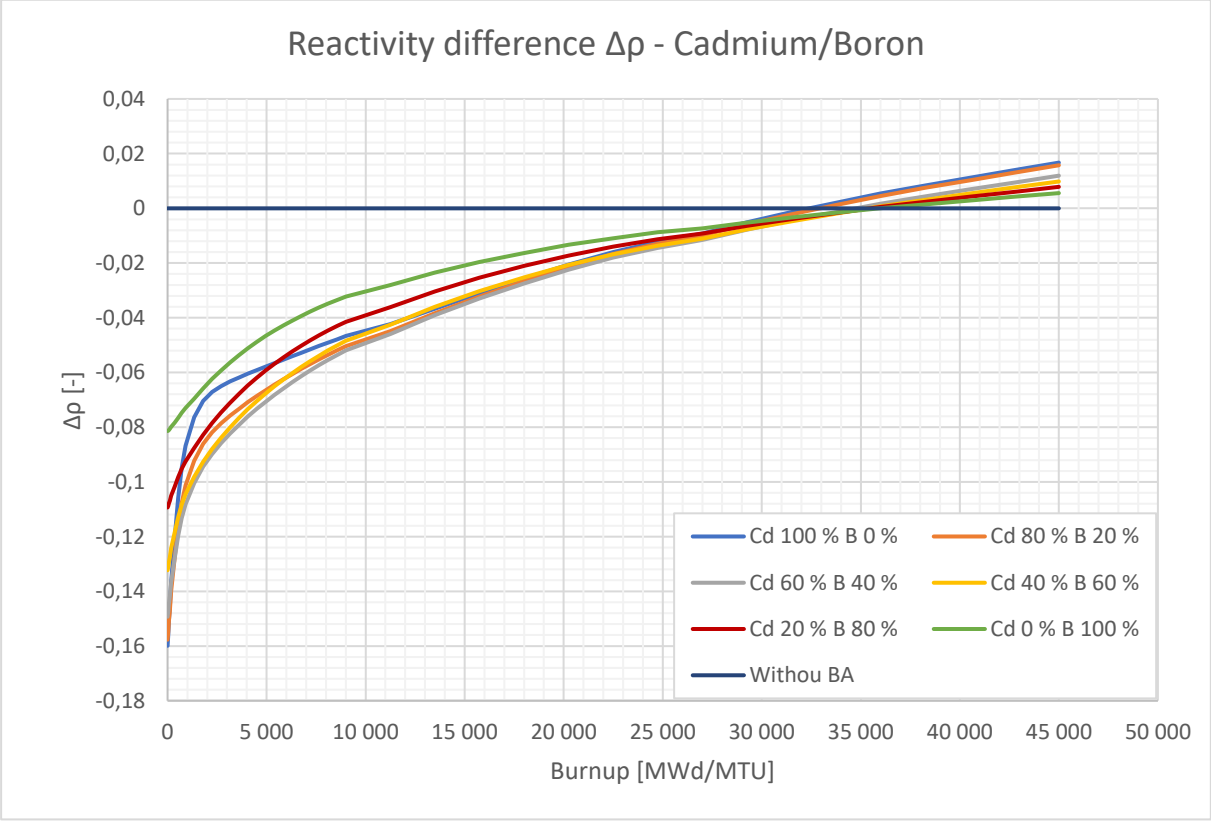


Graph 15. Multiplication factor - Cadmium/Boron

The multiplication behavior shows that the cadmium/boron combination is suitable for the burnable absorber. At the beginning, the drop of multiplication factor caused by cadmium can be seen. Then there is the peak which was set to $k_{eff} = 1.2$, some of the concentrations are

even below this line, so the compensation is better. After the peak, the constant decrease began. All the curves are nicely shaped and close together, and at the end, all of them are above the “Without BA” curve. This is a desirable state, due to the release of reactivity and thus the possibility of prolongation of the fuel cycle.

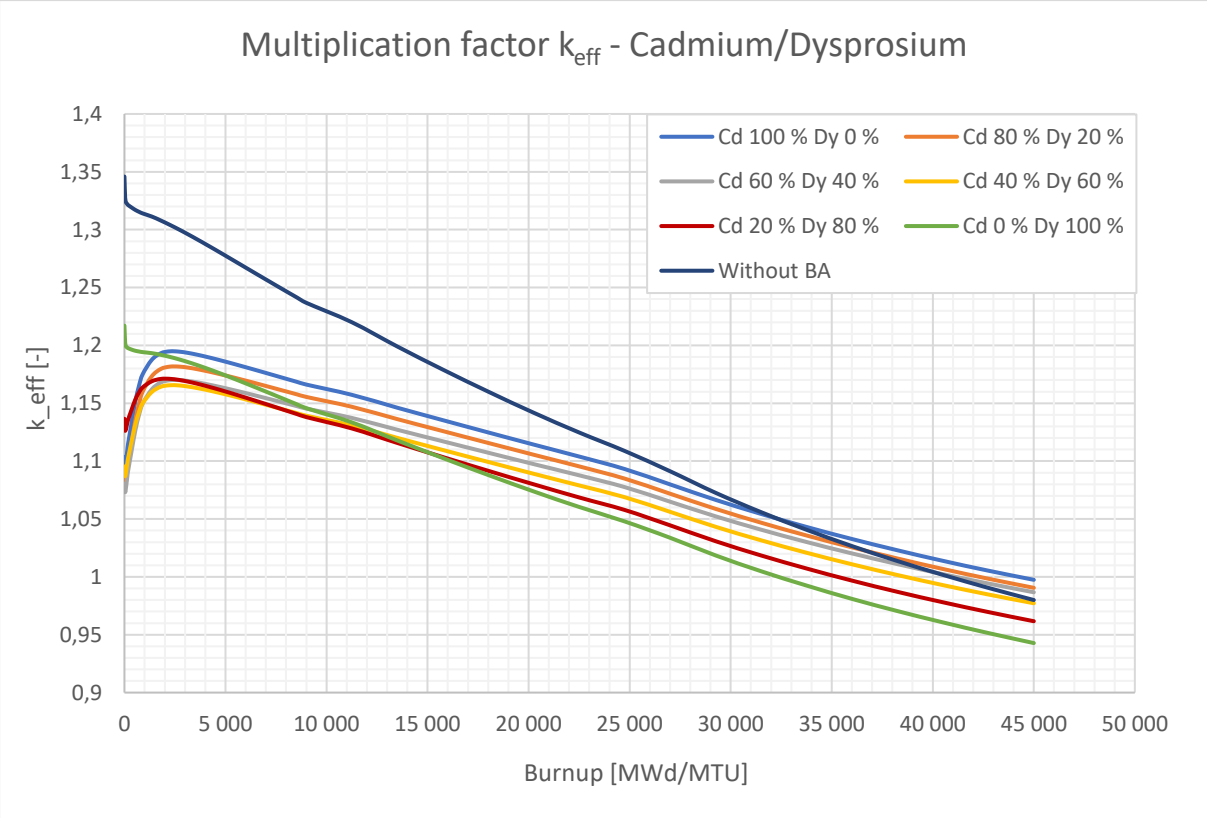
From the Graph 16. Reactivity difference - Cadmium/Boron below the reactivity difference for cadmium/boron burnable absorber can be seen. Again, there is the large drop of reactivity at the beginning and then the reactivity starts to increase smoothly. This smoothness is the merit of the slow burnable absorber, in this case, boron. The more boron there is in the BA, the smoothest the shape of the curve is. On the other hand, from the concentration 40 % of boron and more, the reactivity compensation decreases. So, in this case, the concentration of 60% Cd and 40 % B would be the most suitable one. As explained above, at the end of the fuel cycle all the curves are above the zero line, thus positive reactivity is released.



Graph 16. Reactivity difference - Cadmium/Boron

Cadmium/Dysprosium

The next combination that was made was the cadmium/dysprosium combination. Again, in this case, cadmium is the fast burnable absorber and dysprosium the slow burnable absorber. The smoothness of the curve is caused by dysprosium and the initial drop of multiplication factor by cadmium. In the Graph 17, it is shown the behavior of multiplication factor for this combination.

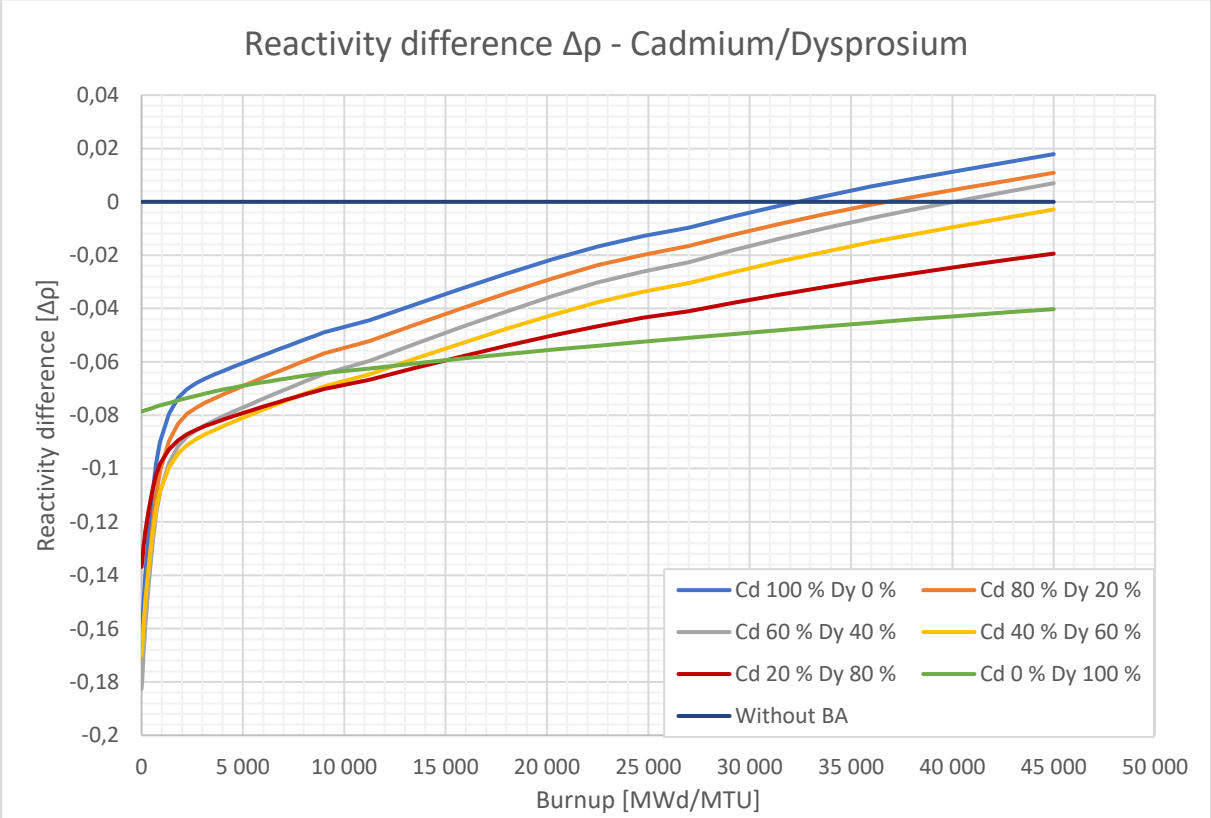


Graph 17. Multiplication factor - Cadmium/Dysprosium

This combination is a bit different from the one before. Cadmium/dysprosium has a similar beginning of the fuel cycle, also there is the initial drop caused by cadmium and then the peak of the multiplication factor. After that, the decrease of the multiplication factor starts, but it is not that smooth. The curves diverge from each other and at the end, there is a quite distance between them. Some of the curves are even below the curve without BA. Basically, only usable curves are with just cadmium, with 80 % of Cd 20 of % Dy and 60 % of Cd 40 % of Dy.

The other concentrations cross the $k_{eff} = 1$ too early, so the fuel cycle would need to be shorter, which is not desirable.

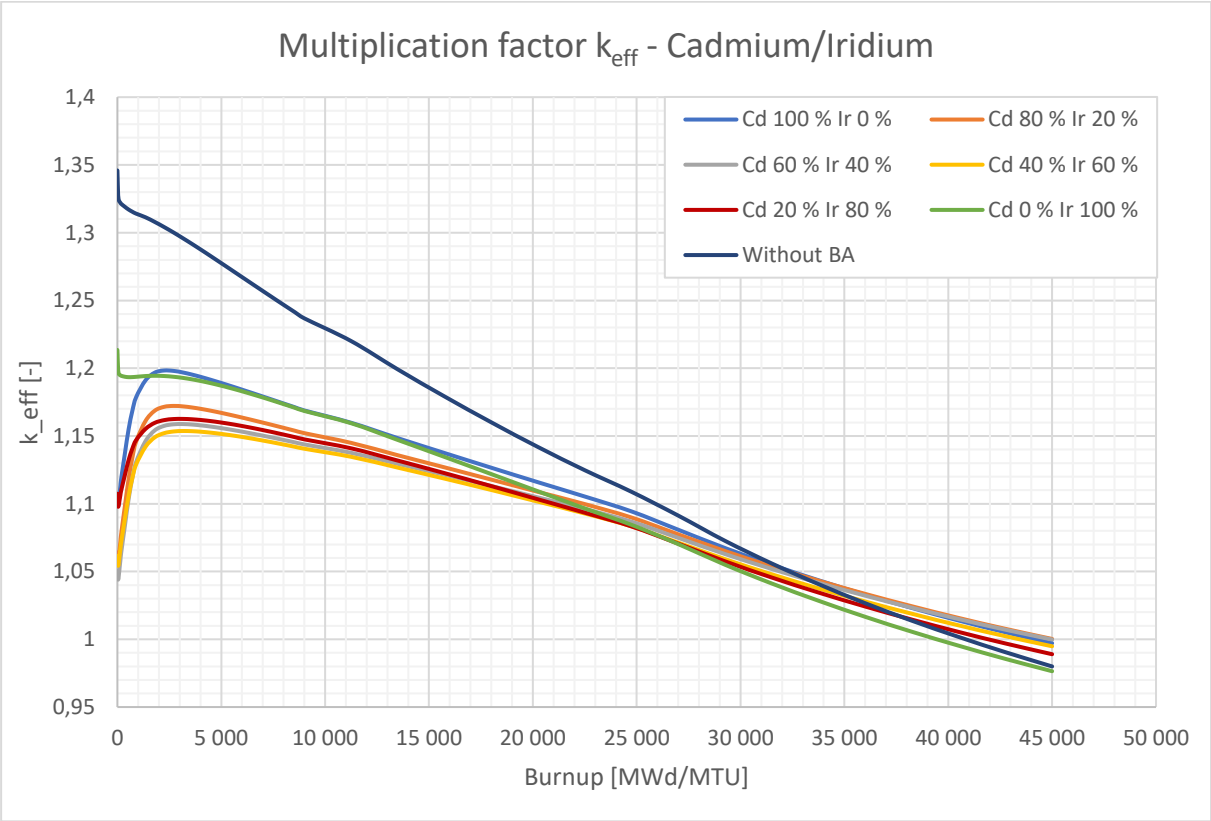
The reactivity difference of cadmium/dysprosium supports the claim stated in the previous paragraph. The initial drop caused by cadmium is appropriate, but the increase of reactivity afterward is not. The curve with just cadmium isn't compensating the reactivity as well as the other concentrations. With increasing concentration of dysprosium, the compensation is better and the curves are crossing the zero-reactivity line later than in the case of just cadmium, so the positive reactivity release is happening further in the fuel cycle. But overall this combination is not suitable for a burnable absorber.



Graph 18. Reactivity difference - Cadmium/Dysprosium

Cadmium/Iridium

Last combination involving cadmium is the cadmium/iridium combination. Again, this absorber is composed of one fast burnable absorber (cadmium) and one slow burnable absorber (iridium). The behavior of multiplication factor for cadmium/iridium combination is shown in Graph 19.

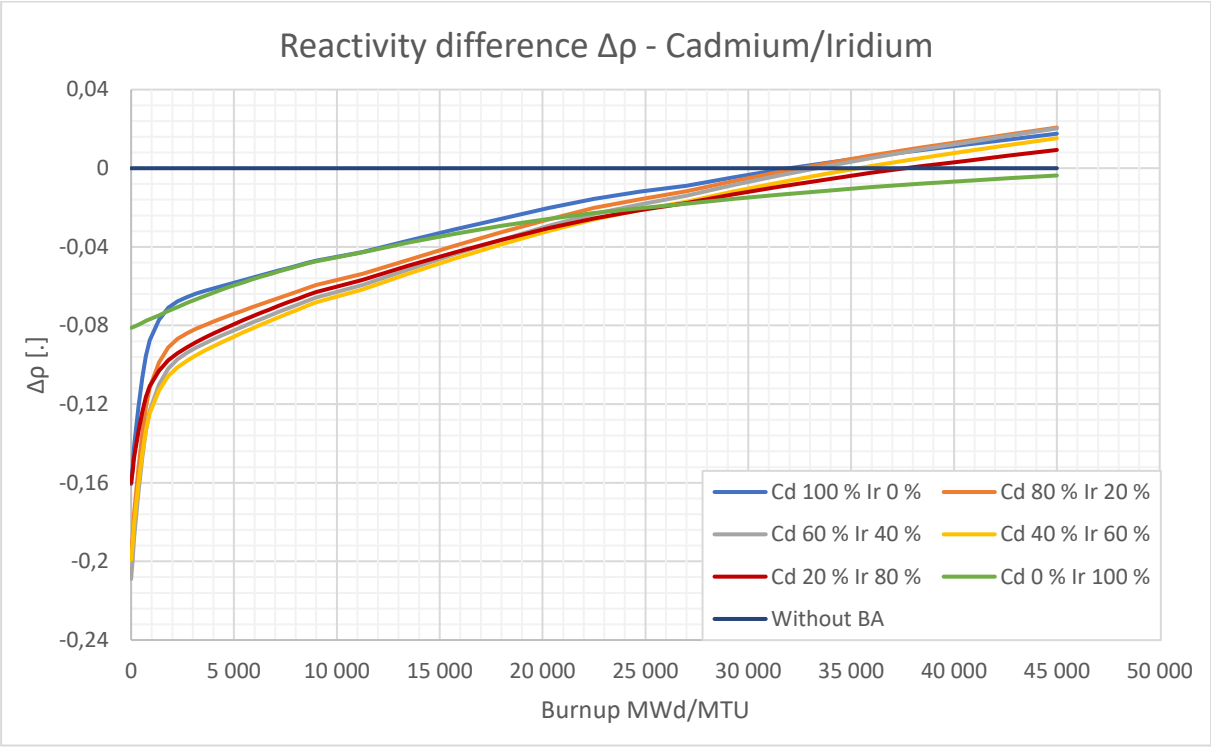


Graph 19. Multiplication factor - Cadmium/Iridium

In the case that is shown above, it can be seen that this combination is appropriate for the burnable absorber. The initial drop is like the cadmium/boron, but it is larger, so the compensation in initial step is better. The peak after the initial step is here lower than in the previous cases, which is also better. The behavior of the decrease after the peak is smooth and constant due to the iridium part of the burnable absorber. The best compensation ability is at the burnable absorber with 40 % of Cd and 60 % of Ir. At the end of the fuel cycle, all curves, except the curve with just iridium, are above the curve without the burnable absorber. This can lead to the prolongation of the fuel cycle.

The reactivity difference shown in Graph 20 is similar to the cadmium/boron case. In this case, the curves are closer together and the initial compensation of reactivity is larger. The curves for BA with 100 % of one element are above the curves where the elements are mixed. This means that the peak after the initial compensation of reactivity is smaller with the mixed burnable absorbers. This is convenient because of the compensation of the peak with boric acid, in the case of mixed burnable absorbers, the compensation can

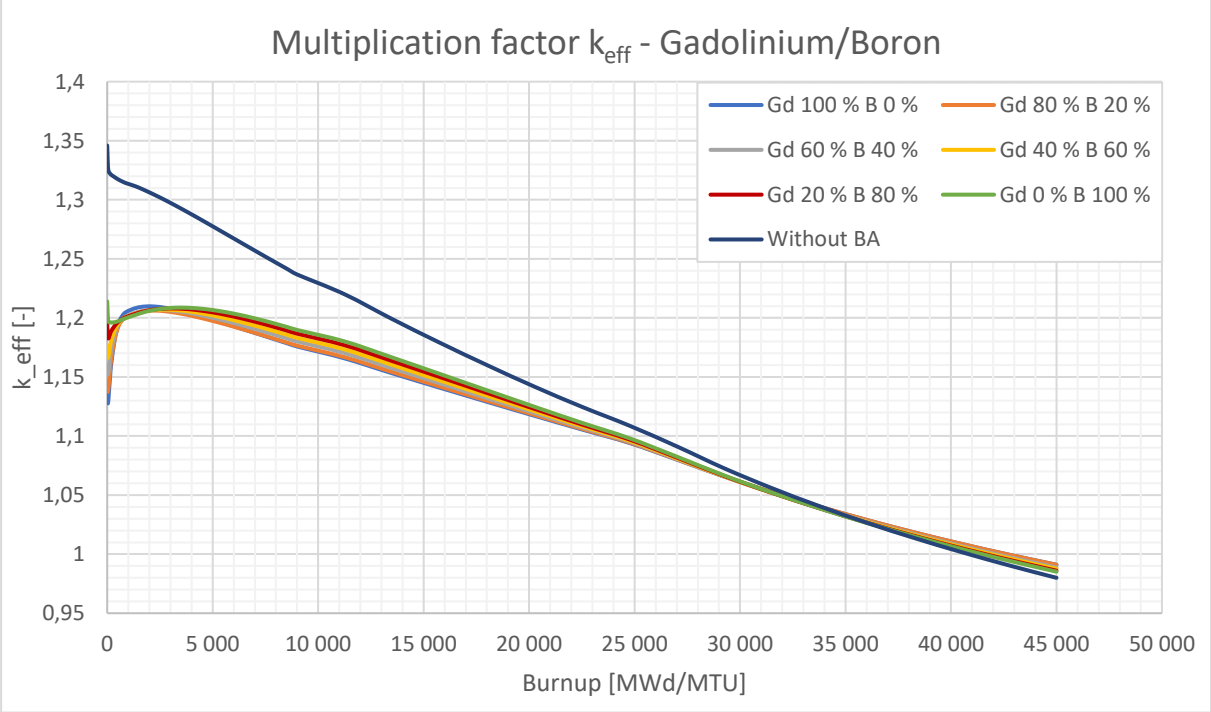
be smaller. At the end of the fuel cycle, except the case with 100 % of iridium, all the other concentrations are above the zero-reactivity line. With increasing fraction of cadmium, the positive reactivity, that is released increases. The most released reactivity is at the concentration 80 % cadmium and 20 % of iridium.



Graph 20. Reactivity difference - Cadmium/Iridium

Gadolinium/Boron

For the next combination, the gadolinium was selected as a fast burnable absorber. The slow burnable absorbers are same as in the previous cases, boron, dysprosium, and iridium. Gadolinium is the element with largest neutron capture cross section from all the elements that was calculated, thus the initial compensation of reactivity is large. Boron, on the other hand, is the slow burnable absorber, so the behavior of multiplication factor is rather smooth. The multiplication factor behavior of gadolinium/boron combination can be seen in Graph 21. Multiplication factor - Gadolinium/Boron

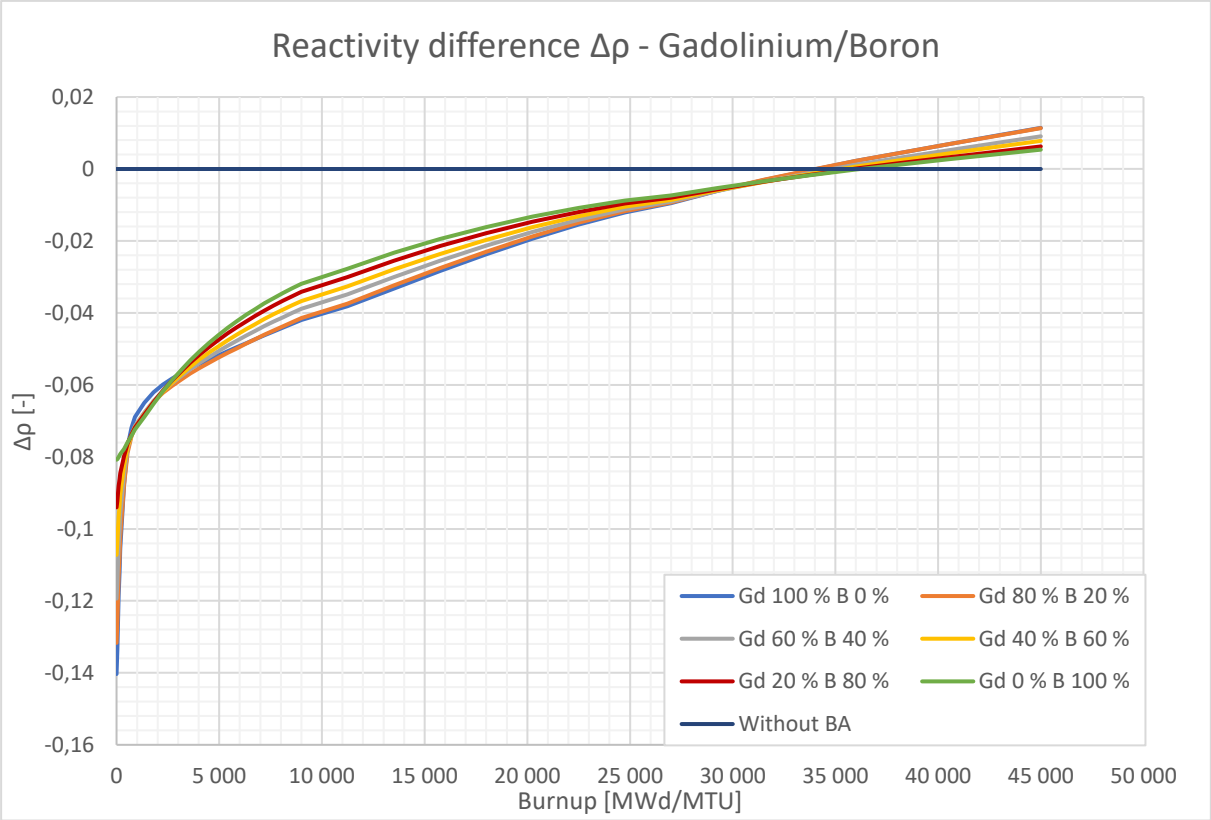


Graph 21. Multiplication factor - Gadolinium/Boron

As it was described in the previous paragraph, the large absorption cross section of gadolinium causes the big multiplication factor drop at the beginning of the fuel cycle. This combination fulfills the condition of $k_{eff} = 1.2$ at burnup $B = 2\,250 \frac{MWd}{MTU}$ best. All the curves are close together and meet in close distance of $k_{eff} = 1.2$. After this peak, the curves start to decrease and diverge, but once the curves reach the maximum diverge point, they start to converge again. They converge very well and basically meets the "Without BA" curve around one point. After this, they start to diverge again, this is desirable, because if the prolongation of the cycle. The curve with 100 % of gadolinium and 0 % of boron is furthest from the "Without BA" curve. With increasing concentration of boron, the curves start to get closer to the curve without burnable absorber, thus the prolongation of the fuel cycle would not be as big as with single gadolinium burnable absorber.

On the following Graph 22, the reactivity difference with gadolinium/boron burnable absorber is shown. In this graph, the initial drop of reactivity can be seen. It is evident that with increasing concentration of boron, this drop is not that large as with the burnable absorber that has just gadolinium. This is caused by the enormous neutron capture cross section of gadolinium. It is shown the increasing of the curves after the initial drop of reactivity and the

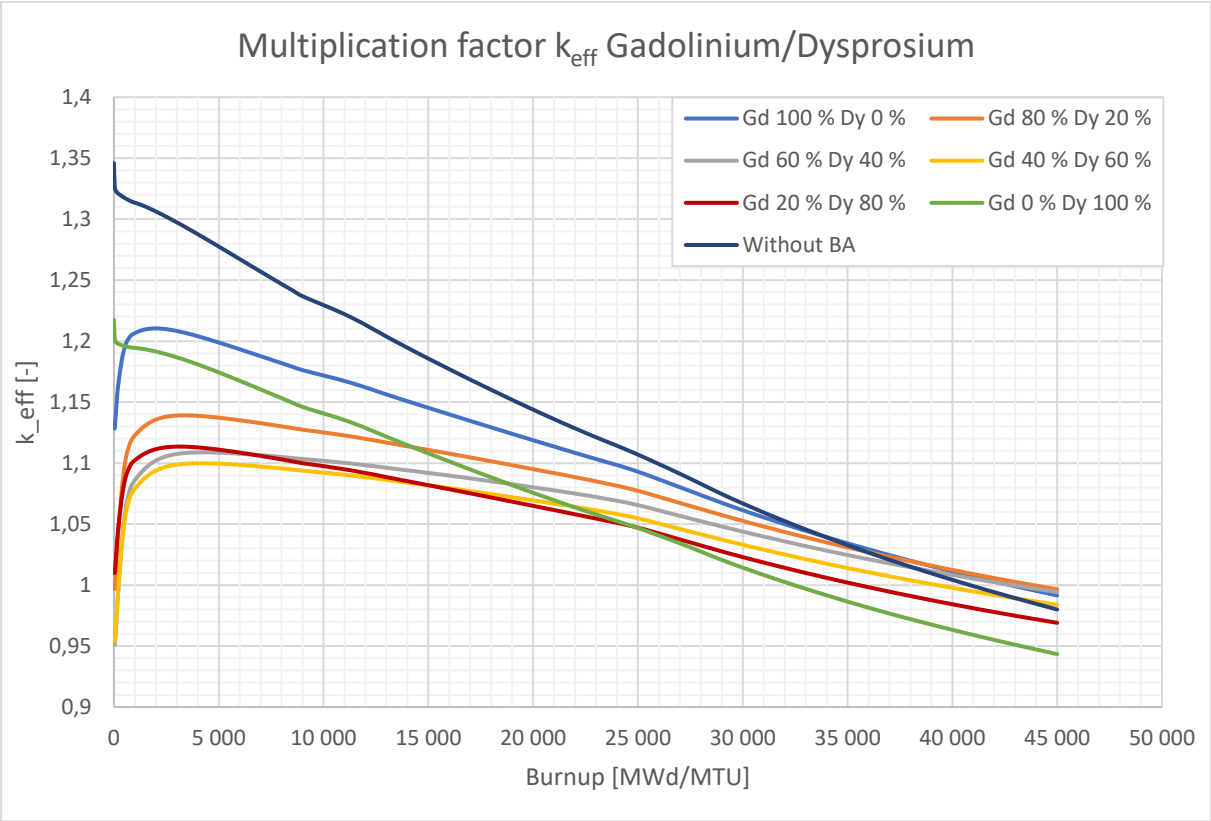
divergence is more evident in this graph than in the previous one. From the reactivity difference behavior is clearer, that the burnable absorber curves meet before they cross the zero-reactivity line. And again, at the end of the fuel cycle, positive reactivity is released.



Graph 22. Reactivity difference - Gadolinium/Boron

Gadolinium/Dysprosium

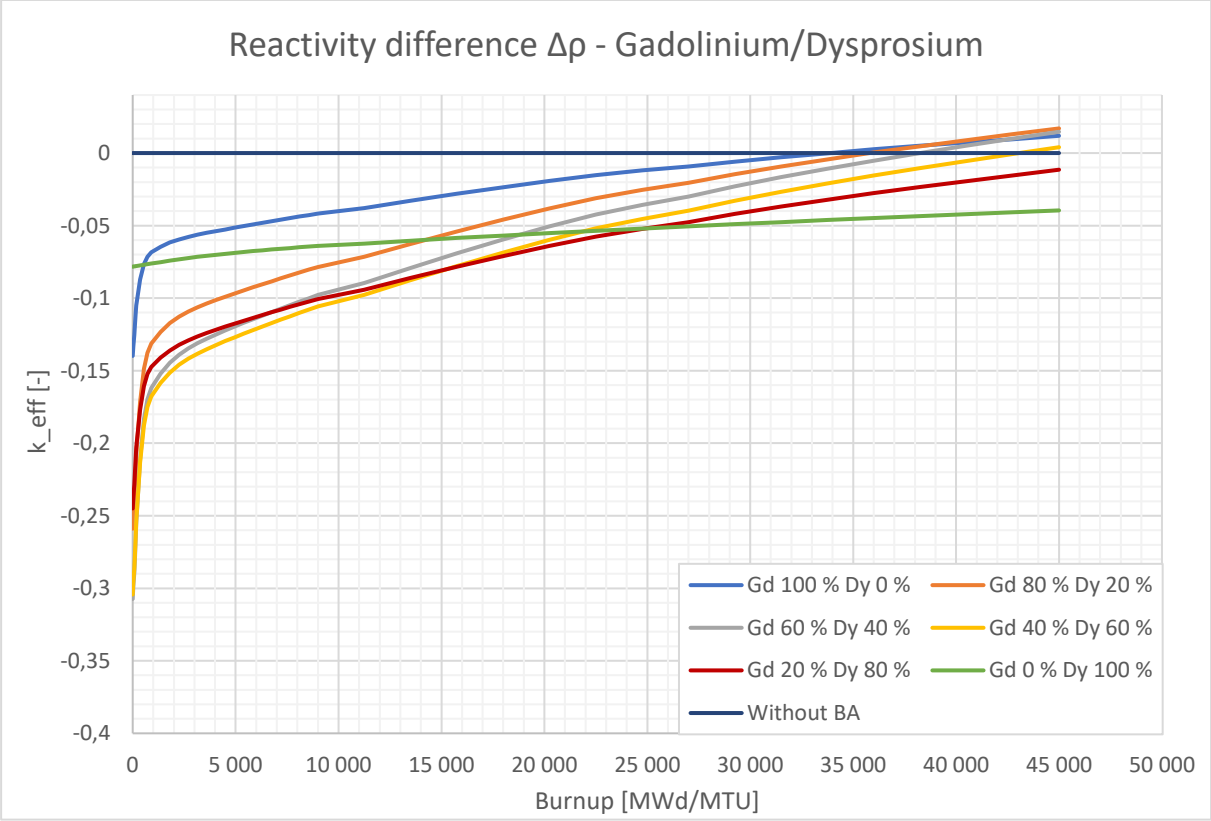
In this part, the combination of gadolinium/dysprosium was calculated. In the previous calculation with cadmium/dysprosium, it was shown that the combination with dysprosium is not suitable for the burnable absorber. The combination with gadolinium could be more suitable, due to the large capture cross section of gadolinium, which could bring the curves together. Also, the initial drop of reactivity should be bigger than in the cadmium/dysprosium combination and at the end of the fuel cycle, it would be appropriate if there would be a positive reactivity release. The behavior of multiplication factor of gadolinium and dysprosium can be found in Graph 23.



Graph 23. Multiplication factor - Gadolinium/Dysprosium

From the graph, it is clear that the prediction was wrong. At the beginning, there is a bigger drop of reactivity than in the cadmium/dysprosium combination, but the curves diverge even worse here. The peak after the initial drop is here lower than the set $k_{eff} = 1.2$, this is good, because the compensation with boric acid could be lower in this case. Even the decrease of these curves is not as steep as in the previous cases. This again means that the behavior of the multiplication factor is smoother and it is not needed to compensate with boric acid or the control rods that much. But the negative in here is that the curves diverge too much, especially after the burnup $B = 25\,000 \frac{MWd}{MTU}$. With increasing concentration of dysprosium, the curves are more in the negative reactivity zone, thus the combinations with more than 60 % of gadolinium has not have the positive reactivity release at the end of the fuel cycle. It can be predicted that with larger burnup some of these curves would be above the curve without burnable absorber, but the positive reactivity release would not be as big as with the combinations that have less concentration of dysprosium. So, with this, probably the best combination for burnable absorber would be the 80 % of gadolinium and 20 % of dysprosium.

Below the Reactivity difference - Gadolinium/Dysprosium is shown. Here it can be seen that the compensation of reactivity is larger in the combinations than in the single element burnable absorber. The initial reactivity drop is biggest in the combination of 40 % gadolinium and 60 % of dysprosium. This drop though is too big and the multiplication factor is below the value of one at the beginning of the fuel cycle. The same problem is with the 60 % Gd and 40 % Dy combination. But in the real operation, this problem could be probably solved by decreasing the concentration of H_3BO_3. From the reactivity difference behavior, also the combination of 80 % Gd and 20 % Dy is the best.

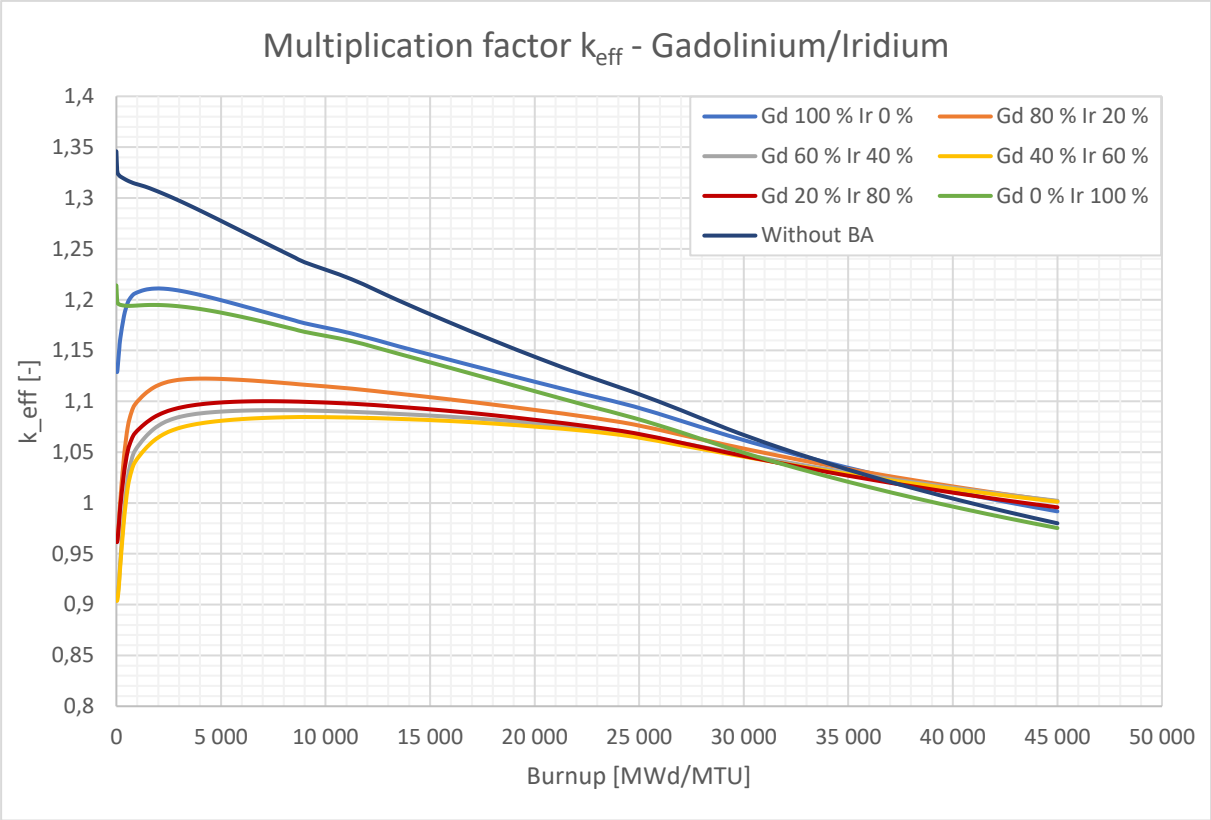


Graph 24. Reactivity difference - Gadolinium/Dysprosium

Gadolinium/Iridium

The last combination of gadolinium is the combination with iridium. Iridium is an element that has not as big capture cross section as boron or dysprosium, thus the curves should be more constant and linear. Of course, there should be a large initial drop of reactivity at the beginning of the fuel cycle, due to the gadolinium, but overall the curves should be more constant, than in the previous cases. It should be like the cadmium/iridium combination, just the

compensation of reactivity should be larger here, because of the gadolinium and its large capture cross section. In Graph 25 the behavior of multiplication factor for the combination of gadolinium/iridium is shown.

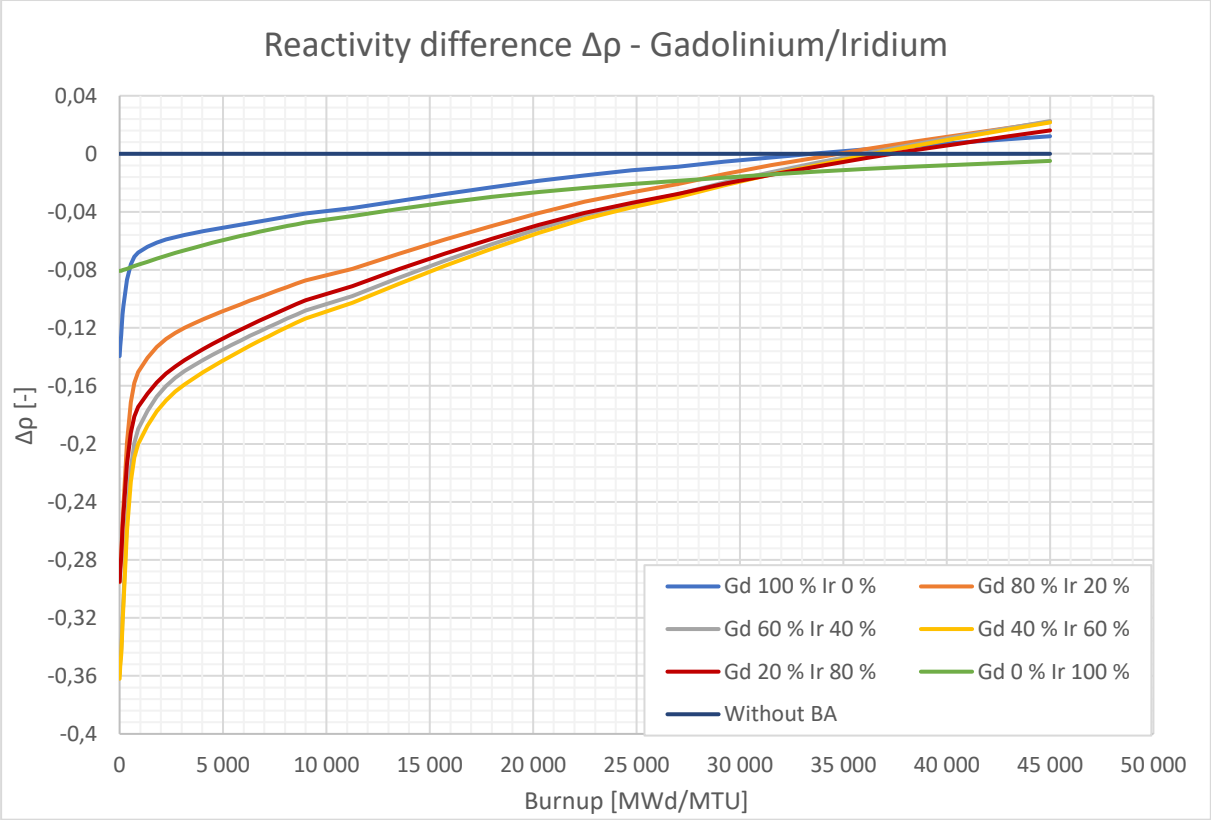


Graph 25. Multiplication factor - Gadolinium/Iridium

The multiplication factor behavior shows that there is a big difference in the compensation of reactivity between single element BA and the double element combination BA. If there is just gadolinium or just iridium, the curves are almost similar, both are around $k_{eff} = 1.2$ in the peak and then decrease. The difference between those two curves is that at the end of the fuel cycle, the burnable absorber curve with just iridium is not above the curve without burnable absorber. Concerning the curves with combinations of those elements, on the first look, the compensation here is larger. The initial drop of reactivity is at some concentrations even below $k_{eff} = 1.0$. Then the increase to the peak stops around the value $k_{eff} = 1.1$ instead of the set value. It is evident that the double element burnable absorber curves have a constant almost linear behavior. This is very useful, because of the concentration of boric acid, in this case it can be lower. The multiplication factor decreases

from 1.1 to 1.0 in 40 000 MWd/MTU, so this combination can be considered as a slow burnable absorber. At the end of the fuel cycle all the curves, except the curve with just iridium, are above the "Without BA" curve and the fuel cycle can be prolonged.

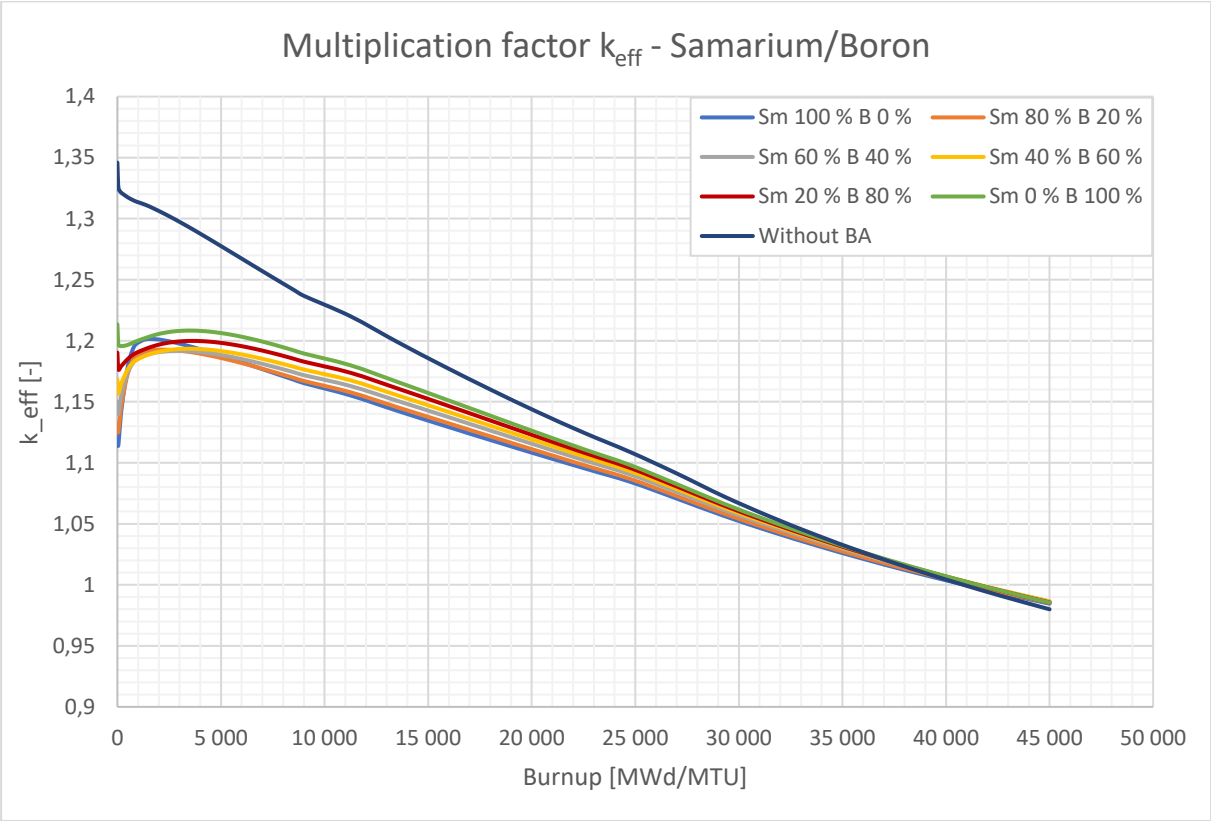
The reactivity difference that can be seen in the Graph 26 confirms the paragraph above. At the beginning of the fuel cycle, there is a big drop of reactivity. This drop is perhaps even too big, the multiplication factor is below one at this point. But this problem can probably be solved by using less H_3BO_3 or by control rods. As it was explained in the previous paragraph the reactivity compensation is larger in the double element burnable absorber specifically, the largest compensation of reactivity is in the combination of 40 % gadolinium and 60 % of iridium. The curves are above the zero-reactivity line at the end of the fuel cycle and thus the positive reactivity is released and the prolongation of the fuel cycle is possible. The only case where the curve is not above the zero-reactivity line is the burnable absorber with 100 % of iridium. But from the shape of the curve, it can be anticipated that it will be above this line if the burnup would be larger.



Graph 26. Reactivity difference - Gadolinium/Iridium

Samarium/Boron

The last combinations were the combinations where as the fast burnable absorber the samarium was used. As the slow absorbers, the same set of elements was used as in the previous cases. Samarium is an element with the second largest capture cross section from the elements that were selected for this calculation. It is expected that at the beginning of the fuel cycle there will be large reactivity compensation. Similar to the one in combinations with gadolinium. The first combination is samarium/boron and the behavior of multiplication factor for this combination can be seen in Graph 27. Multiplication factor - Samarium/Boron.

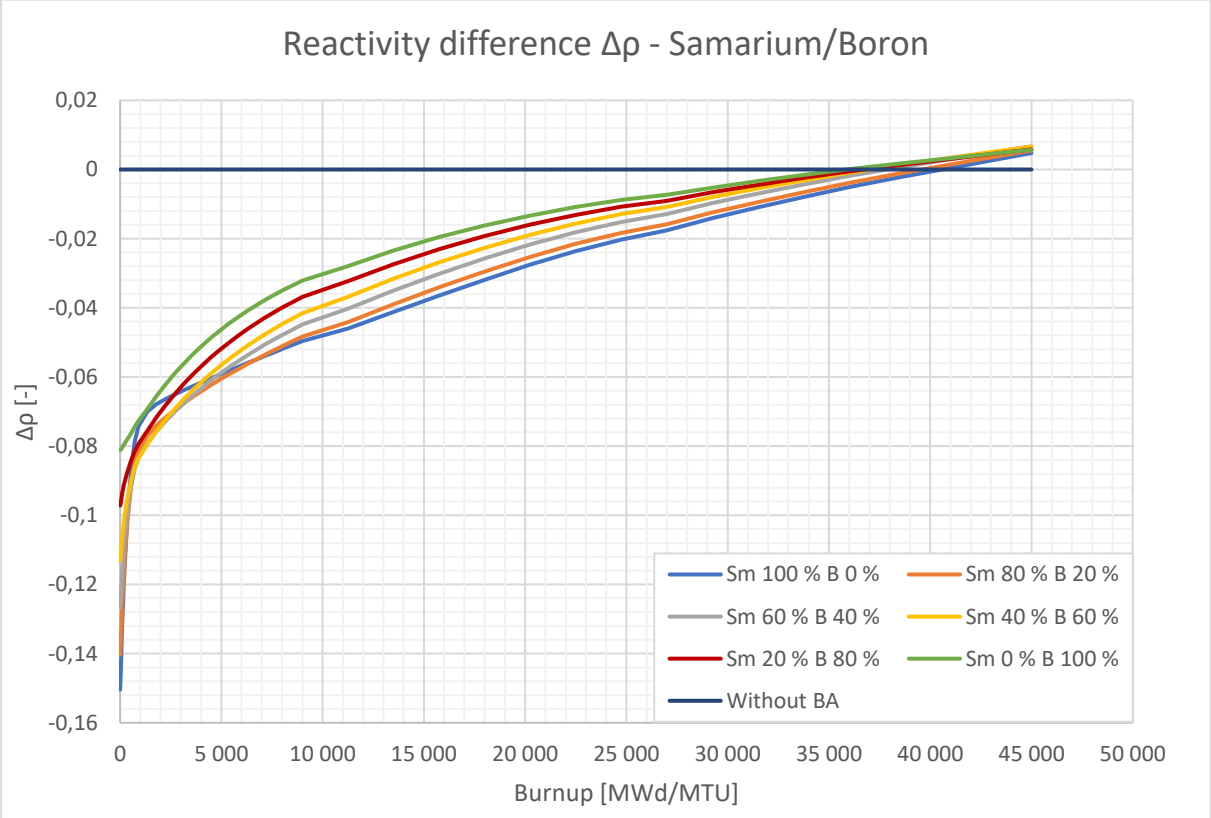


Graph 27. Multiplication factor - Samarium/Boron

The initial drop of multiplication factor is not as big as it was expected. The largest initial drop in this combination has the single element burnable absorber with just samarium and it did not drop below the $k_{eff} = 1.1$. With increasing concentration of boron, the initial drop is smaller and the concentration of 100 % of boron has just a little drop just below the $k_{eff} = 1.2$ value. The behavior is like the combination of gadolinium/boron, the curves meet at the peak, and then diverge to the maximum value, which is around burnup

$B = 12\,000 \frac{MWd}{MTU}$, and after that they start to converge again and they meet almost at one point. This point is above the curve without burnable absorber and thus it means all the curves ends above this curve. So, the prolongation of the fuel cycle is possible.

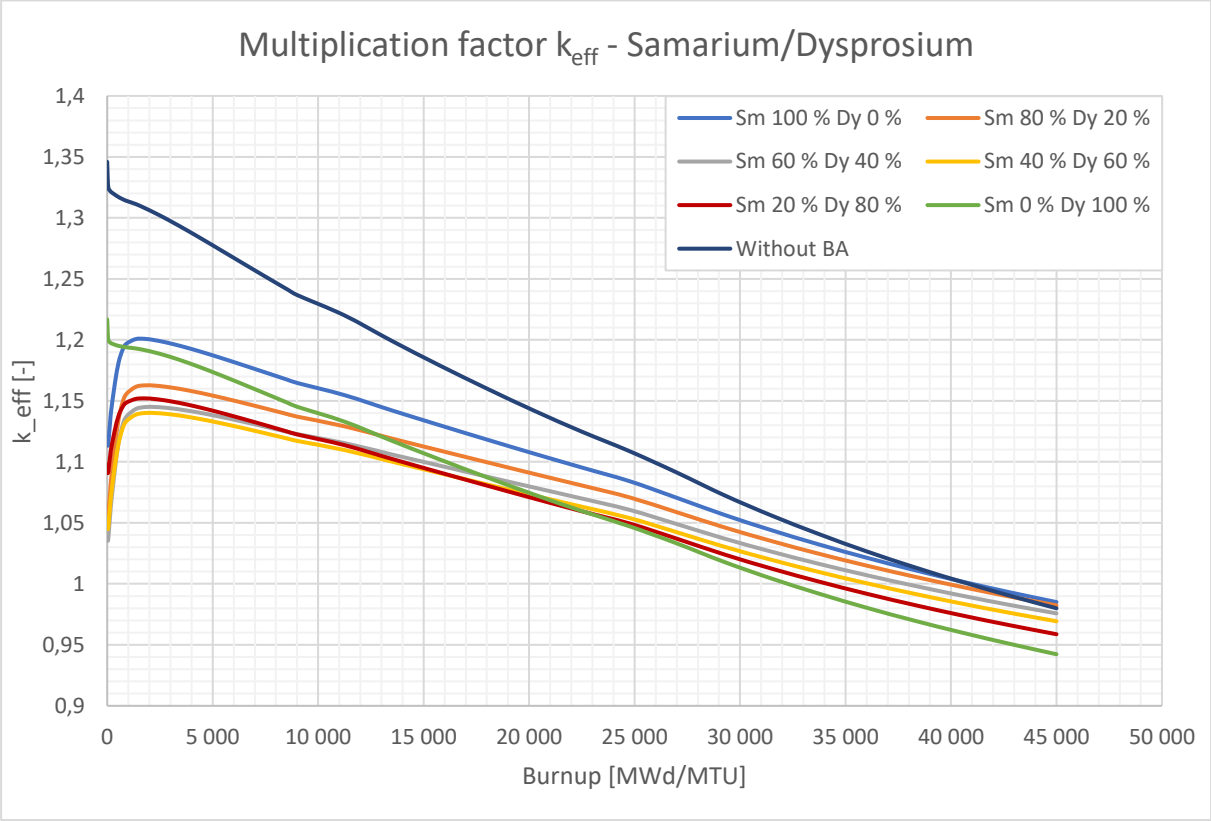
The reactivity difference, which can be seen in Graph 28, shows the divergence of individual curves more clearly. After the initial drop of reactivity, the curves start to increase till they reach the peak showed in the multiplication factor behavior. The increase of reactivity is smoother with increasing concentration of boron. For example, the concentration 20 % of Sm and 80 % of B has a smooth increase in comparison to the 100 % of Sm BA, where there is a rapid increase from the initial drop compensation. After the maximum divergence, the curves start to converge again and, as described in the previous paragraph, they meet at one point. This point as above zero reactivity line so the positive reactivity is released and the prolongation of the fuel cycle is possible.



Graph 28. Reactivity difference - Samarium/Boron

Samarium/Dysprosium

The second combination of samarium is the combination with dysprosium. The previous two combinations showed itself as not appropriate for the burnable absorber. This combination would probably not be suitable as well. But it is not suitable for this type of reactor, for example, the ACR will use dysprosium as a burnable absorber in their new fuel.

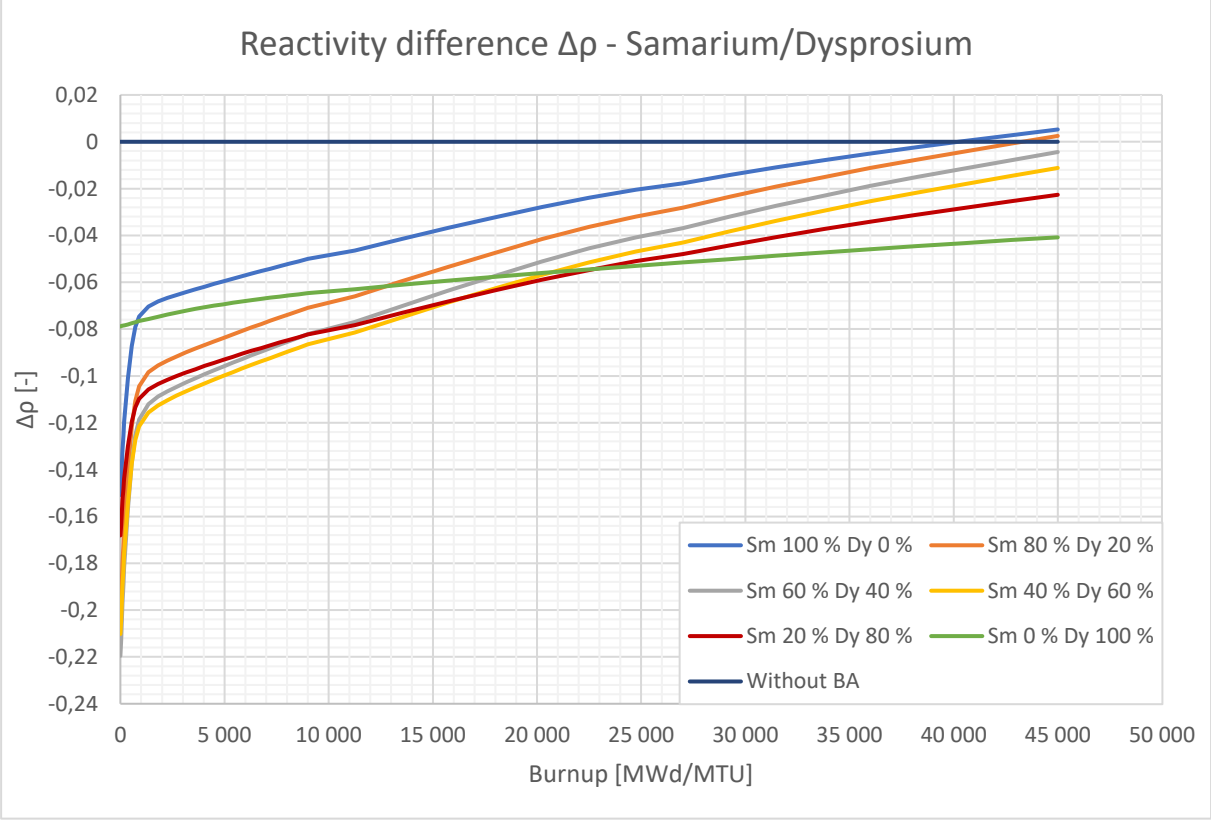


Graph 29. Multiplication factor - Samarium/Dysprosium

The behavior of multiplication factor for the combination of samarium/dysprosium can be found in Graph 29. As it was predicted the behavior is like the cadmium/dysprosium and gadolinium/dysprosium combinations. The peak, in this case, is somewhere between $k_{eff} = 1.14 - 1.16$. The compensation is better than cadmium/dysprosium but worse than gadolinium dysprosium. There is also the initial drop of reactivity here, it does not go under $k_{eff} = 1$ so the decrease of boron acid is not needed. After the peak, the curves start to decrease and diverge. At the end of the fuel cycle, they are below the curve without burnable absorber. Only the burnable absorber with 100 % of samarium and the combination of 80 % samarium and 20 % of dysprosium are slightly above. It can be expected that with a

higher burnup, even the other curves will get slightly above “Without BA” curve but the reactivity release will be small. So once again, this combination is not suitable for the burnable absorber.

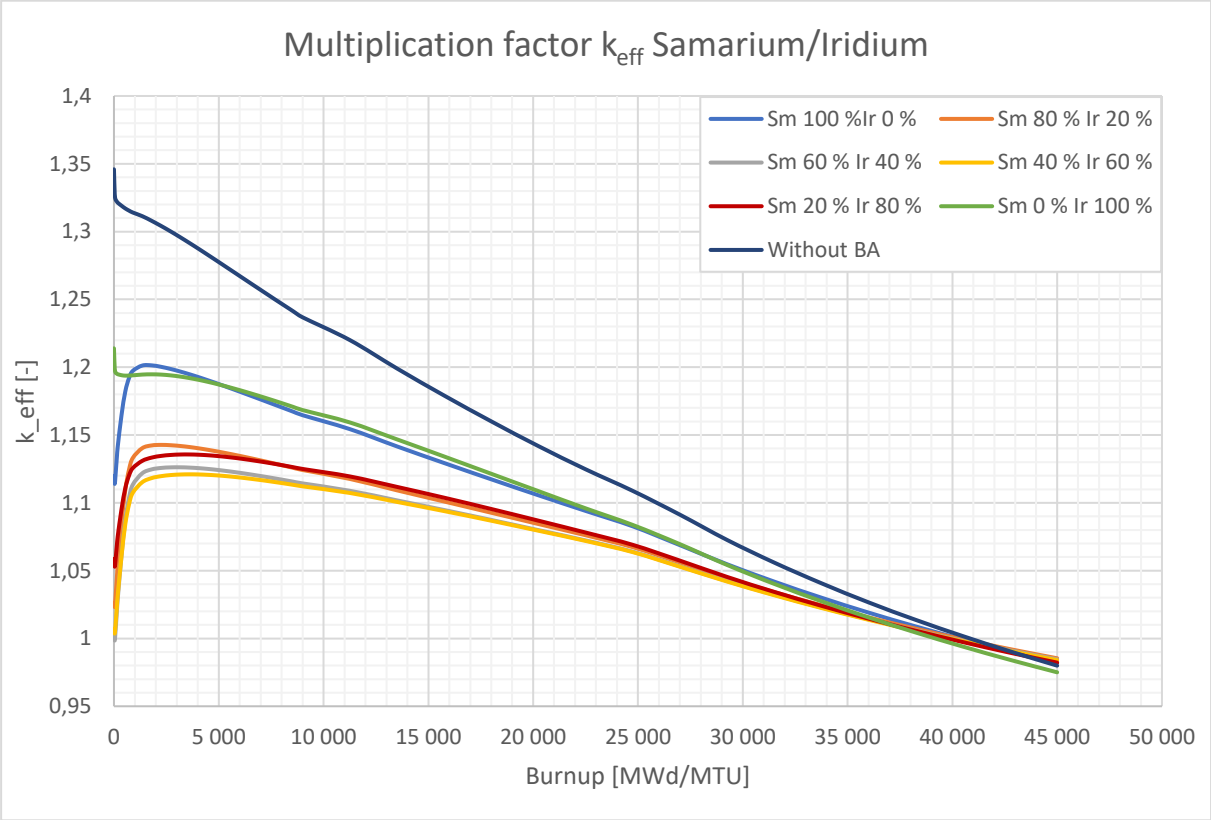
On the first sight of Reactivity difference - Samarium/Dysprosium, it can be seen that the behavior is not as smooth as it was in the case of samarium/boron. After the initial drop of reactivity, it can be seen the rapid increase. This increase lasts to burnup approximately $B = 1\,000\,\frac{MWd}{MTU}$ and then the increase is not that fast. In this part, the curves start to diverge and the reactivity increases constantly. From this graph, the end of the fuel cycle is seen better and it is evident that the curves with 100 % of samarium and 80 % of samarium and 20 % of dysprosium are above the zero-reactivity line. As described before, the other curves would probably get above this line also but higher burnup is needed.



Graph 30. Reactivity difference - Samarium/Dysprosium

Samarium/Iridium

The last combination is the combination of samarium with iridium. Iridium has the lowest capture cross section from the selected elements so the multiplication factor behavior should be smooth. The part of the fast burnable absorber here, represents the samarium, this element, on the other hand, has the second largest capture cross section, thus at the beginning, there should be a large initial compensation of reactivity. The behavior of multiplication factor is shown in Graph 31.

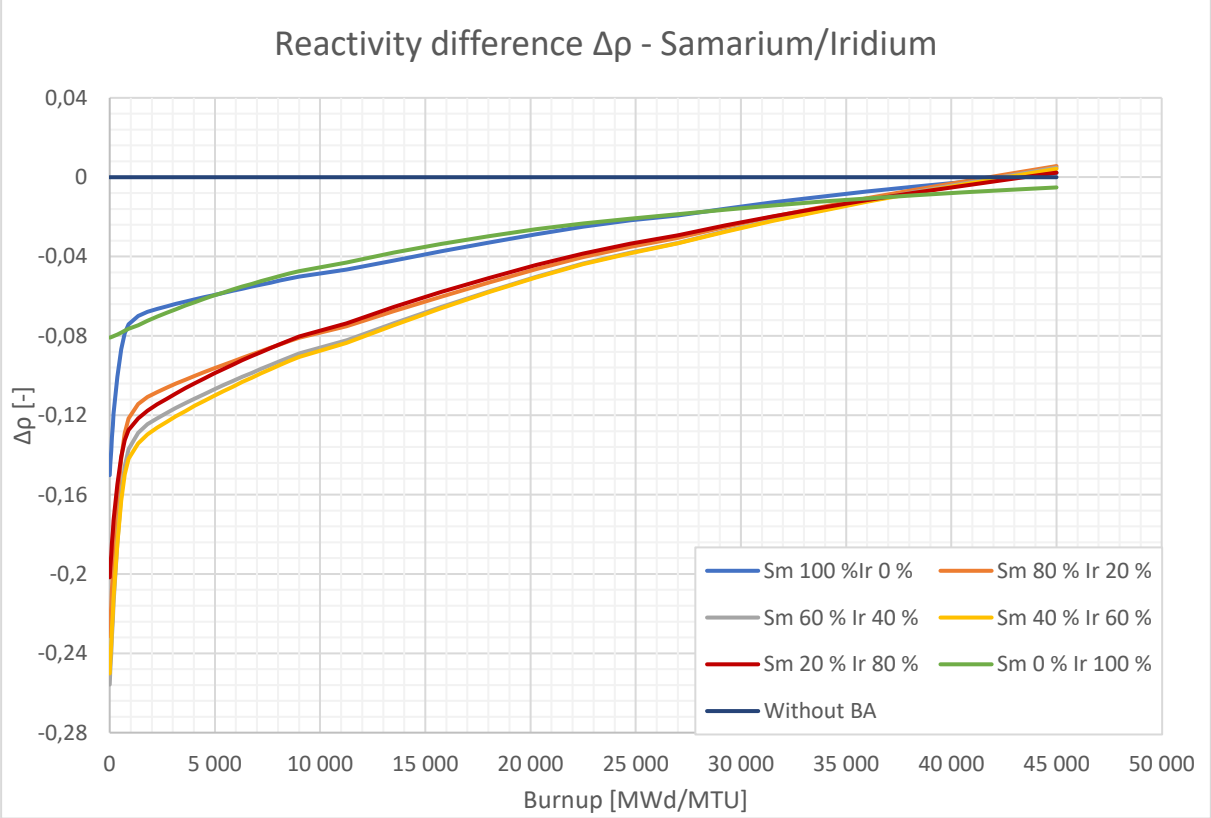


Graph 31. Multiplication factor - Samarium/Iridium

From the graph above it is clear that the samarium makes the large initial drop of reactivity. This drop is not the biggest of all combinations, at the beginning the multiplication factor is around one. This means the reduction of H_3BO_3 is not necessary in this case. In comparison with the burnable absorber with 100 % of samarium or 100 % of iridium, a large decrease of the peak can be observed. In the case of this combination, the peak is somewhere around $k_{eff} = 1.13$ and with the single element BA is around $k_{eff} = 1.2$. After the peak, the almost constant decrease begins, the curves are nicely shaped and they converge to one

meeting point. At the end of the fuel cycle, the curves are slightly above the curve without burnable absorber, thus the fuel cycle can be prolonged. Only exception makes the curve with just iridium, which ends below this curve.

The reactivity difference, which can be seen in Graph 32, is like the gadolinium/iridium. The difference here is that the initial compensation of reactivity is not that big and the curves are less above the zero-reactivity line, so less positive reactivity is released. But due to the smaller compensation of reactivity at the beginning, the decrease of boric acid is not necessary. The prolongation of the fuel cycle is possible but probably to a lesser extent than gadolinium/iridium.



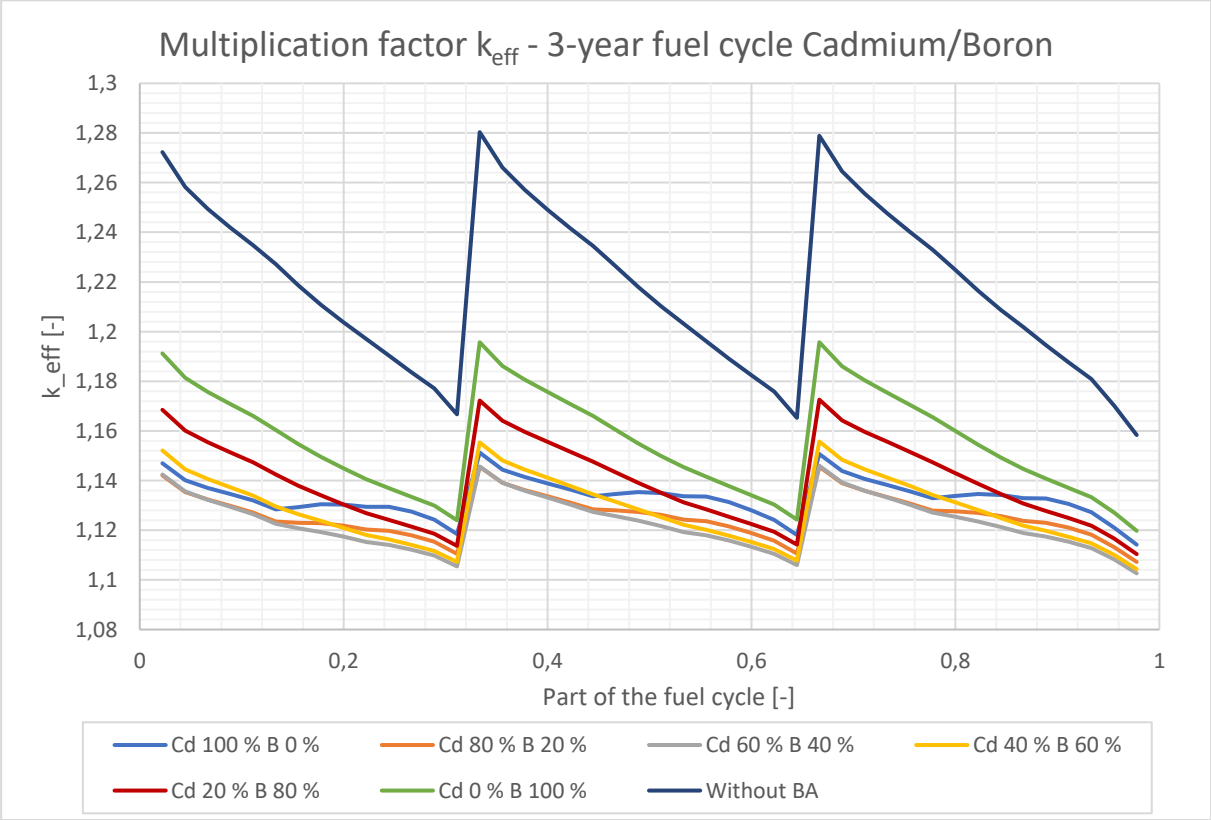
Graph 32. Reactivity difference - Samarium/Iridium

7.2 Selected combinations in the 3, 4, 5-year fuel cycle

Today, most of the power plants are using 3, 4, or 5-year fuel cycle, thus the multiplication factor behavior graph for 3, 4 or 5-years fuel cycle was made. From the group of 9 combinations, just 5 was selected for this part. Namely, the selected ones are Cadmium/Boron, Cadmium/Iridium, Gadolinium/boron, Samarium/boron and Samarium/Iridium. Other combinations were not suitable for the use as a burnable absorber, thus they are not shown here.

Cadmium/Boron

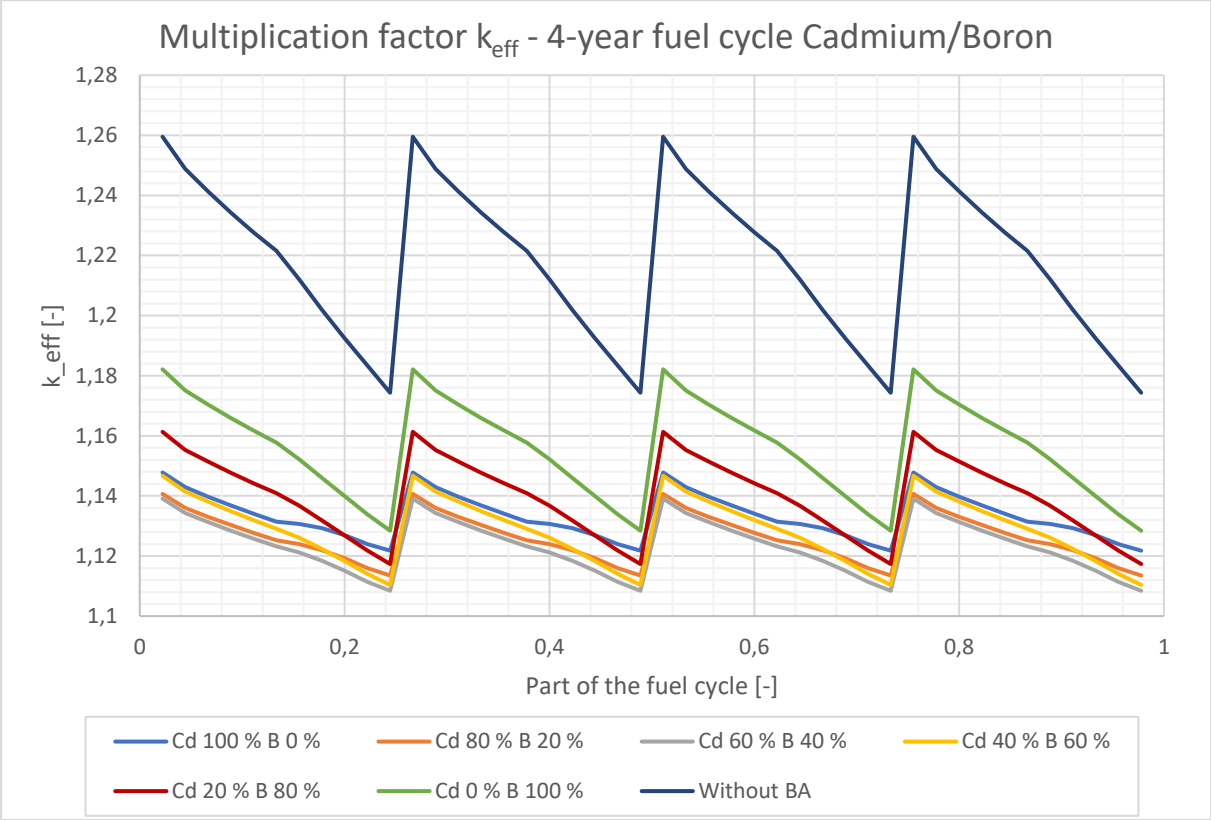
On following graphs, the behavior of multiplication factor of cadmium/boron combination is shown. The 3-year fuel cycle can be seen in Graph 33.



Graph 33. Multiplication factor (3-year fuel cycle) - Cadmium/Boron

The compensation of reactivity is best with the combination of 60 % Cd and 40 % B. The worst combination for reactivity compensation, in this case, is the combination with 100 % of boron. Also, this combination has a large peak between the end of one part of the fuel cycle and

beginning of the new one. It is desirable that these peaks would be as low as possible. In that case, it would be possible to use less amount of boric acid to compensate the excess reactivity.

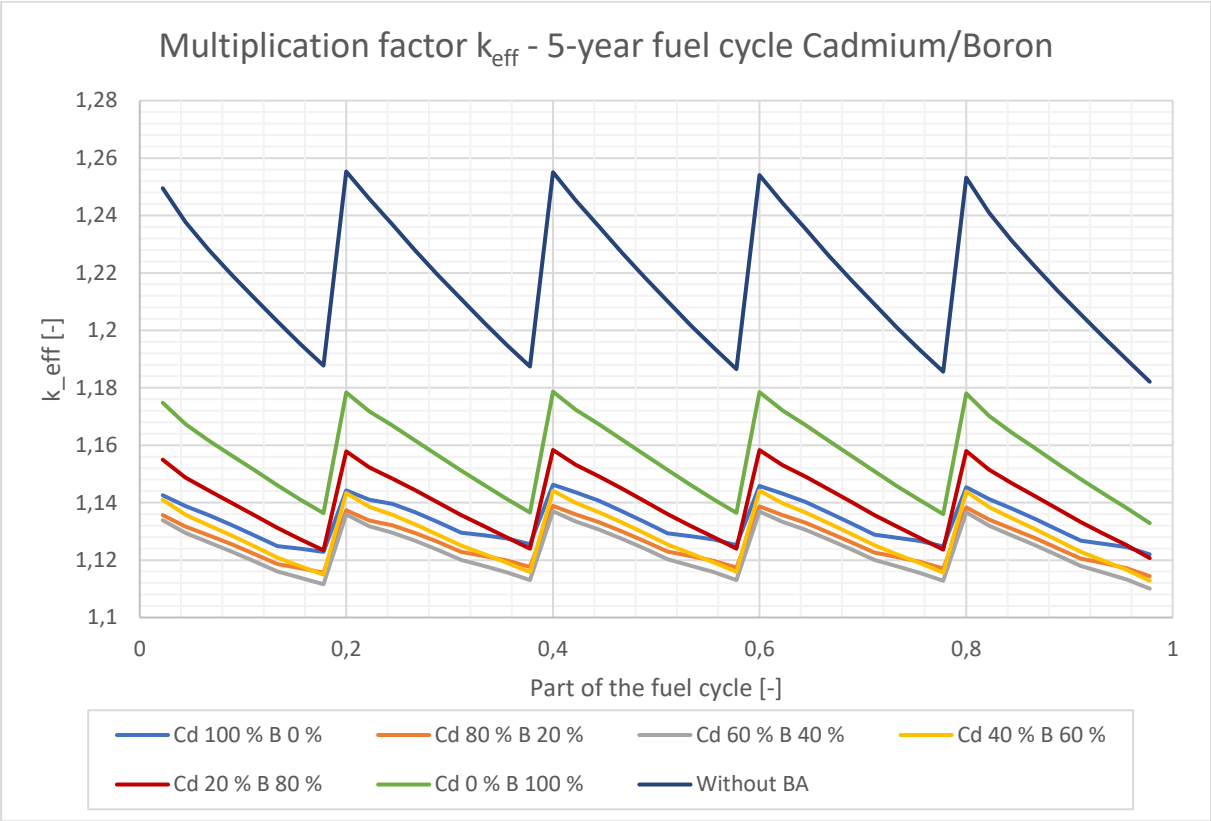


Graph 34. Multiplication factor (4-year fuel cycle) - Cadmium/Boron

In the case of the 4-year fuel cycle (Graph 34), it can be seen on the first sight, that the reactivity compensation is better and the peaks between the fuel changes are lower. Again, the best compensation provides the combination of 60 % Cd and 40 % B. The graphs also show that all the curves are close together, the only exceptions are the combinations with 100 % of boron and the combination with 80 % of boron and 20 % of cadmium. This is caused by the fact that boron is a slow burnable absorber and thus the compensation is slower.

Using a 5-year fuel cycle (Graph 35) results in even better reactivity compensation and lower peaks between the fuel changes than in the case of the 4-year fuel cycle. Once again, in this case, the best reactivity compensation is made by the combination of 60 % Cd and 40 % B.

From the point of reactivity compensation and peaks between the fuel changes, it is best to use the 5-year fuel cycle.

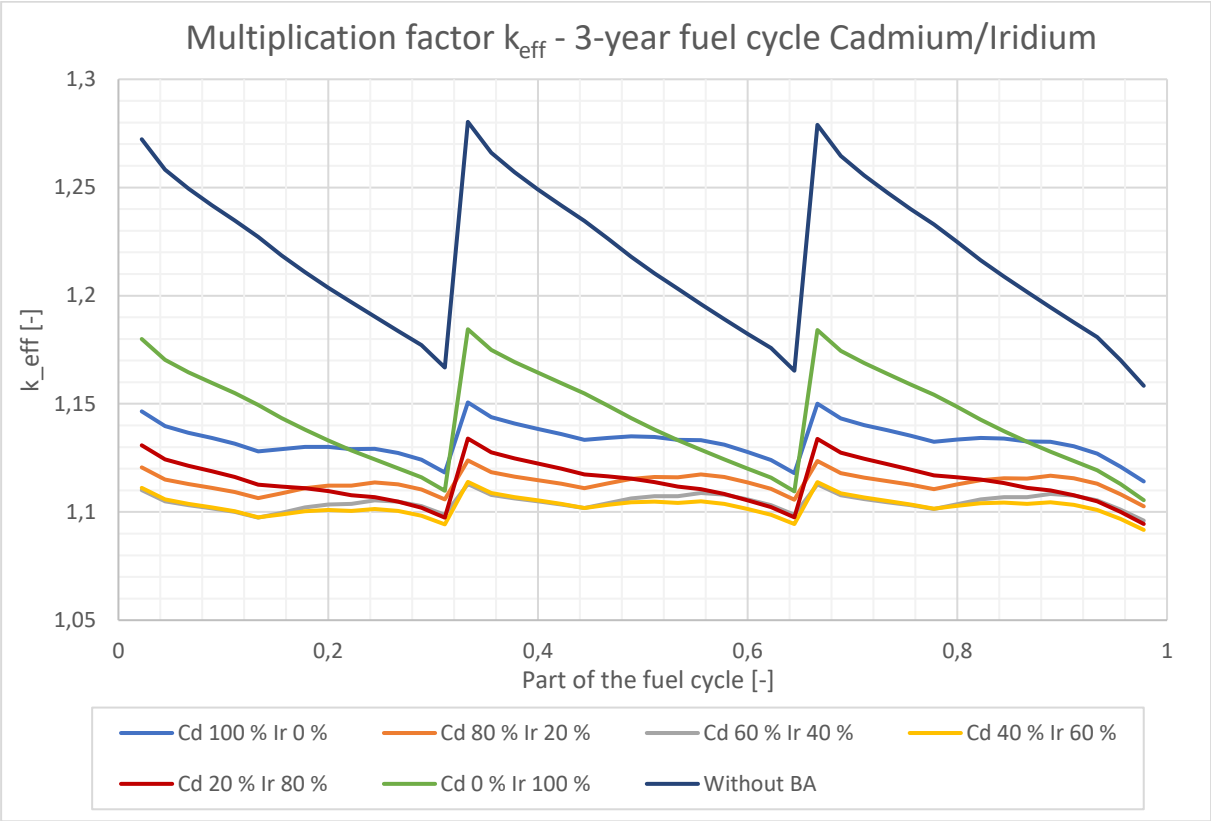


Graph 35. Multiplication factor (5-year fuel cycle) - Cadmium/Boron

Cadmium/Iridium

The next combination with cadmium as a fast burnable absorber is the cadmium/iridium combination. The role of the slow burnable absorber is here taken by iridium. Iridium has the lowest capture cross section from the selected elements. On the following graphs, it can be seen the multiplication factor behavior for each fuel cycle.

The 3-year fuel cycle, which can be seen on Graph 36, shows that the best combinations, in the means of reactivity compensation are the combination of 60 % Cd, 40 % Ir and 40 % Cd, 60 % Ir. These two combinations copy one another and there is just slight difference between them at the end of one part of the fuel cycle. The main difference against the cadmium/boron combination is the height of the peaks. In the case of cadmium/iridium, there is a significant peak reduction, which is desirable. On the other hand, it can be spotted, that the curves are not as close together as in the case of cadmium/boron.

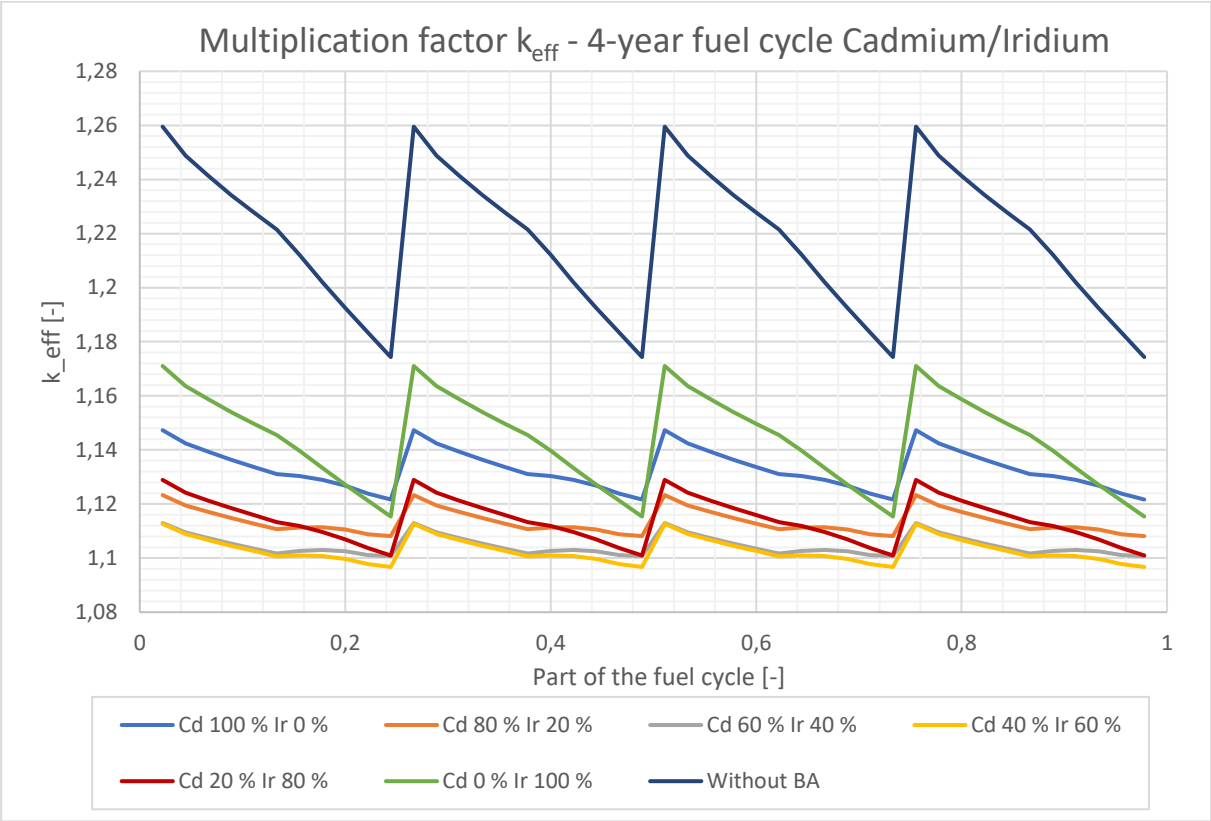


Graph 36. Multiplication factor (3-year fuel cycle) - Cadmium/Iridium

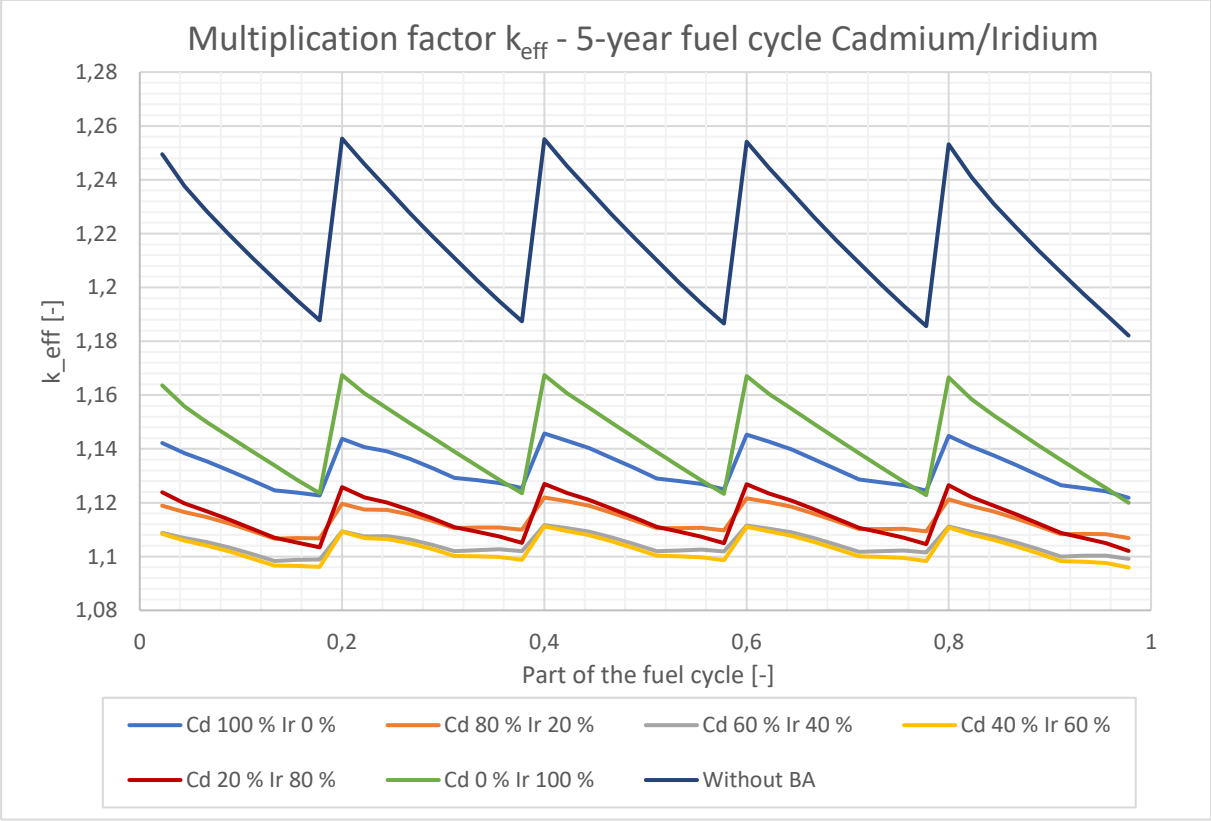
Regarding the 4-year fuel cycle (Graph 37), the reactivity compensation is again better. The best compensation is made by the 60 % Cd 40 % Ir and 40 % Cd 60 % Ir combination, same as in the previous case. The peaks between the end of one part of the fuel cycle and beginning of another are also lower here. The shape of the curves is similar to the 3-year fuel cycle. From the shape of the curves it can be spotted that in the first part of the curve the fast burnable absorber works, and in the second part, the action of the slow burnable absorber takes its place.

In the Graph 38, the 5-year fuel cycle can be seen. In the comparison with the 4 and 3-year cycle, the compensation of reactivity is better in this case. The peaks are again even lower and the whole curves are smoother. Best reactivity compensation and lowest peaks have again the combinations of 40% Cd, 60 % Ir and 60 % Cd, 40 % Ir. Overall it could be said that the slow absorber iridium makes the curves smoother and the peaks lower.

This combination looks rather good, especially the 5-year fuel cycle. It could be use less amount of boric acid, even less than in the previous case.



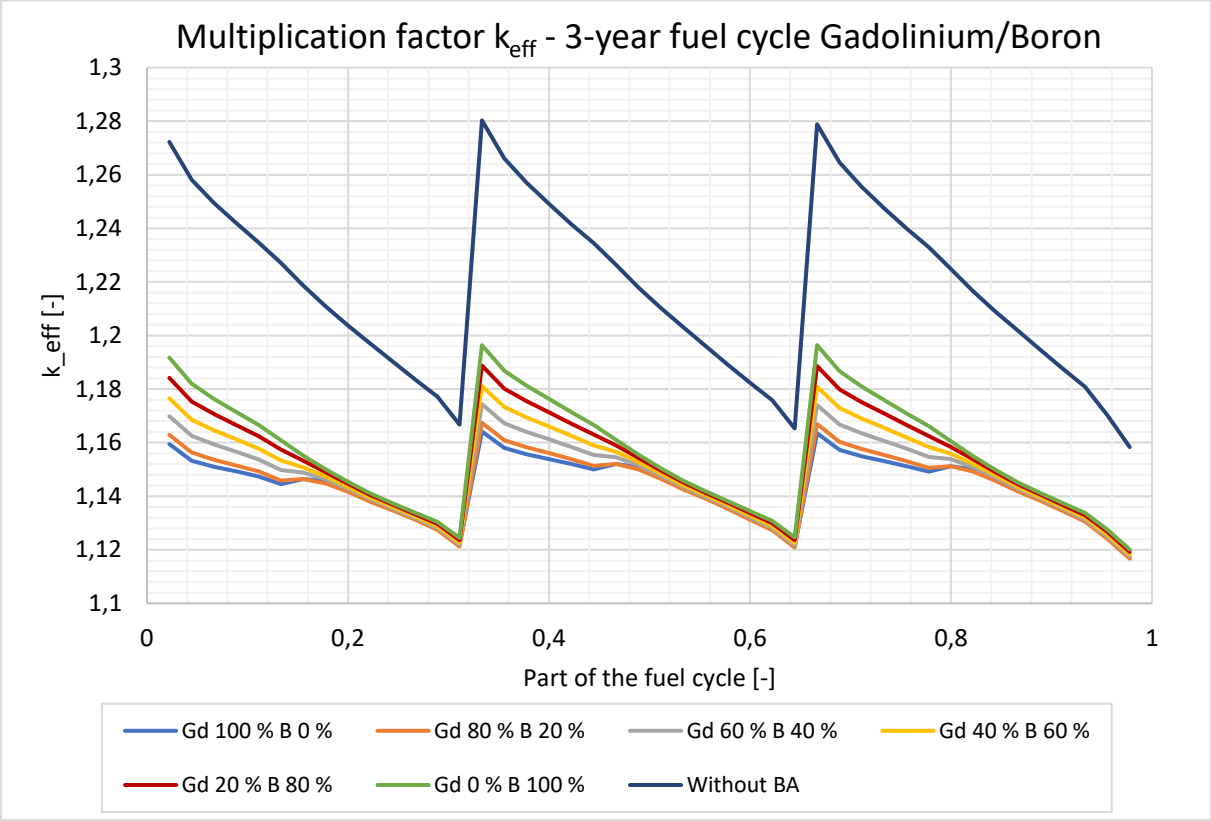
Graph 37. Multiplication factor (4-year fuel cycle) - Cadmium/Iridium



Graph 38. Multiplication factor (5-year fuel cycle) - Cadmium/Iridium

Gadolinium/Boron

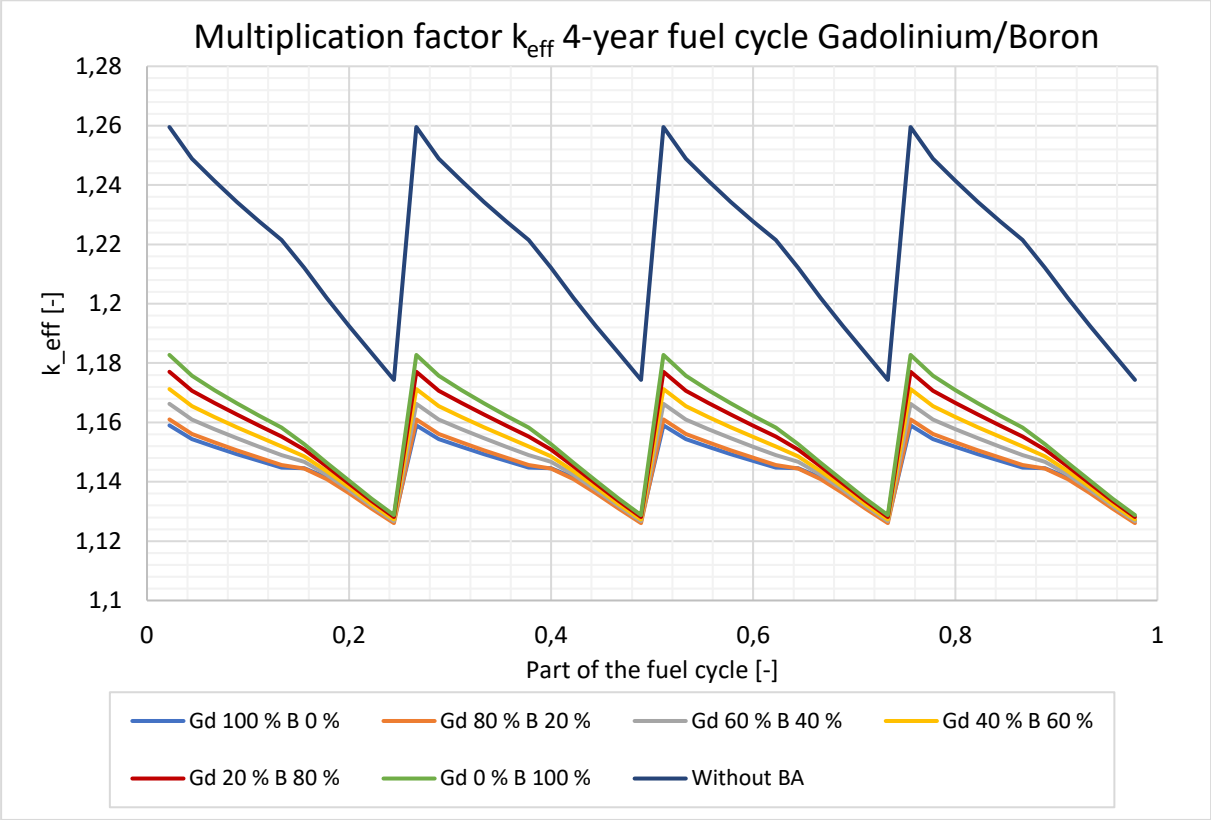
Another combination that was suitable for the use as burnable absorber was the gadolinium/boron combination. This combination uses gadolinium as fast burnable absorber and boron as the slow one. On the further graphs, the multiplication factor behavior of this combination can be found.



Graph 39. Multiplication factor (3-year fuel cycle) - Gadolinium/Boron

From the Graph 39, it is clear that the difference between each concentration is mainly in the first half of the curves. After the first half, the curves intend to converge into almost one point. The first half, where the gadolinium works, has a different excess reactivity compensation. In this case, it could be seen that the best initial compensation has the burnable absorber, where just the gadolinium is used. For this combination, it would be better to use just single element BA and not to mix the gadolinium with boron. On the other hand, the second half of those curves end in points that are very close together. This could be used in the designing of the core. It would be possible to use a different concentration of this combination in a different position of the core. So, the initial compensation would be different but at the end of the

certain part of the fuel cycle the curves would meet at one point, Then the power distribution in the reactor would be better.

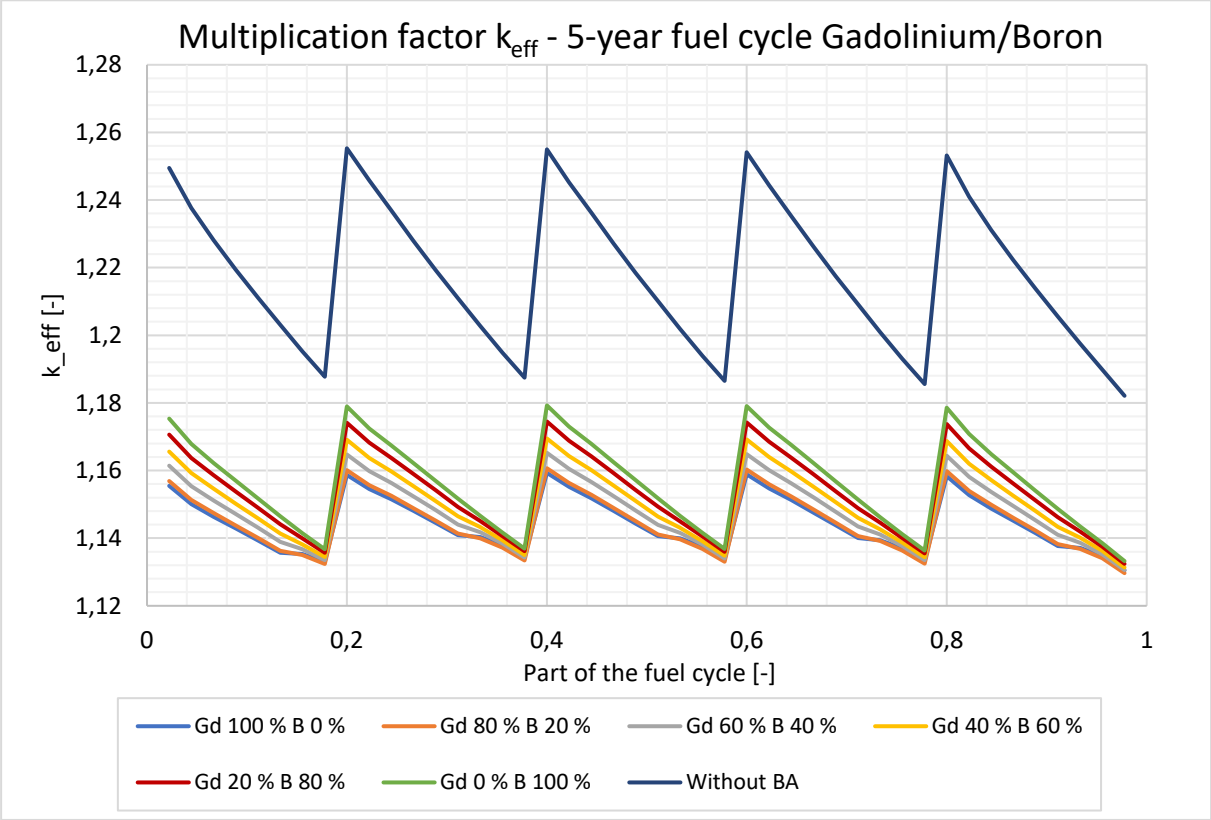


Graph 40. Multiplication factor (4-year fuel cycle) - Gadolinium/Boron

The situation is similar for the 4-year fuel cycle (Graph 40). At the beginning, there is a difference in the initial reactivity compensation, again the best compensation provides the single element BA with the use of gadolinium. And then after approx. two thirds the curves start to converge similarly to the 3-year fuel cycle. In the case of the 4-year fuel cycle, the individual parts of the fuel cycle are shorter, so the ending points are as close together as they are in the previous case. This is also the reason why the part where gadolinium work is longer here.

Regarding the 5-year fuel cycle (Graph 41), the situation is again the same. The reactivity compensation is better, and the difference in the initial reactivity compensation can be observed as well. Since the individual parts of the fuel cycle are even shorter than in the case of 4- year fuel cycle, the part where gadolinium works take about five sixths of the curve. That is also the reason why at the end of the individual part the curves are not as close together as

they are in the previous cases. As it was described before, the best reactivity compensation provides the single element BA with the use of gadolinium.

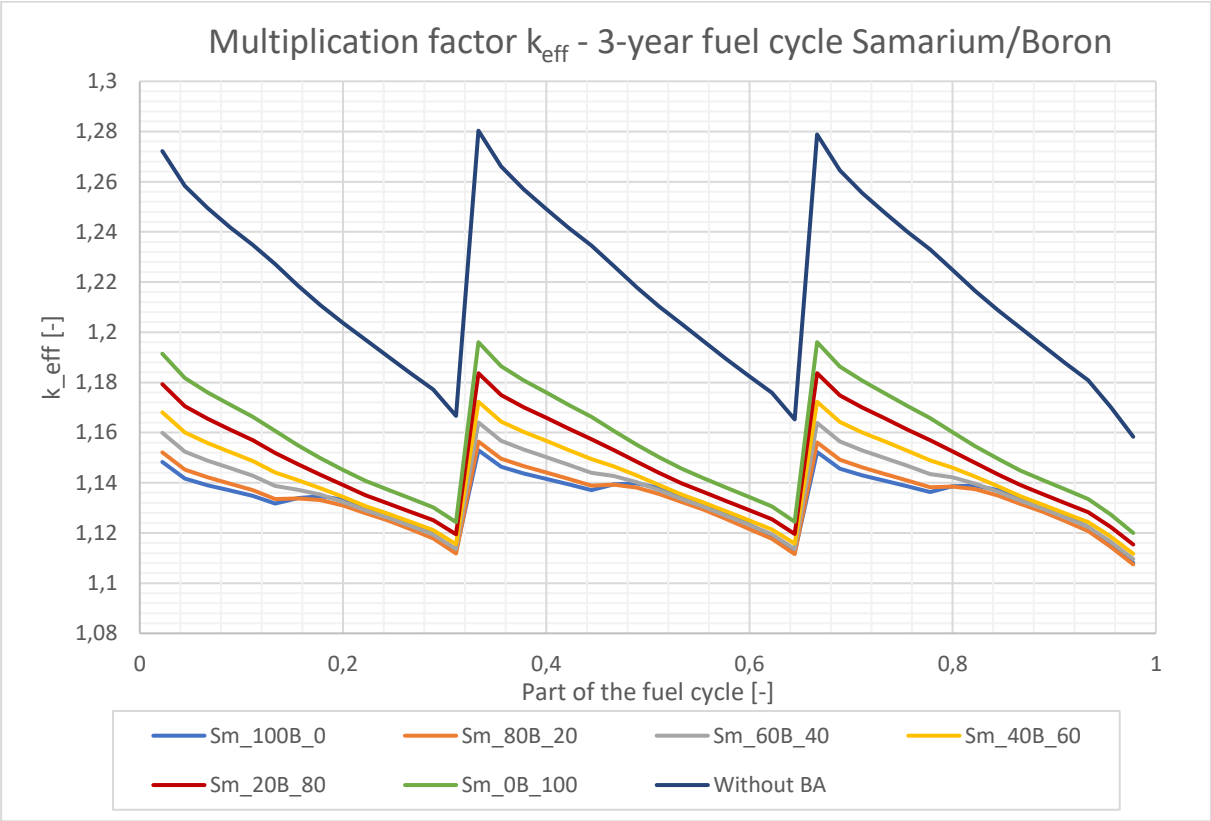


Graph 41. Multiplication factor (5-year fuel cycle) - Gadolinium/Boron

Samarium/Boron

For the next two combinations, the samarium is used as the fast burnable absorber. In this case, as the slow burnable absorber, the boron is used. Both elements have a large capture cross section. The behavior of multiplication factor can be found in following graphs.

The 3- year fuel cycle, shown in Graph 42, has a similar behavior as the gadolinium/boron combination. At the beginning, there could be seen the initial reactivity compensation, caused mainly by the samarium, and in the second part of the curves, the intention to converge into one point. This second part is caused by the boron in the combination. It can be seen, that the curves are not that close together as they are in the case of gadolinium/boron. Also, it can be observed that the best initial compensation is made by the samarium itself.

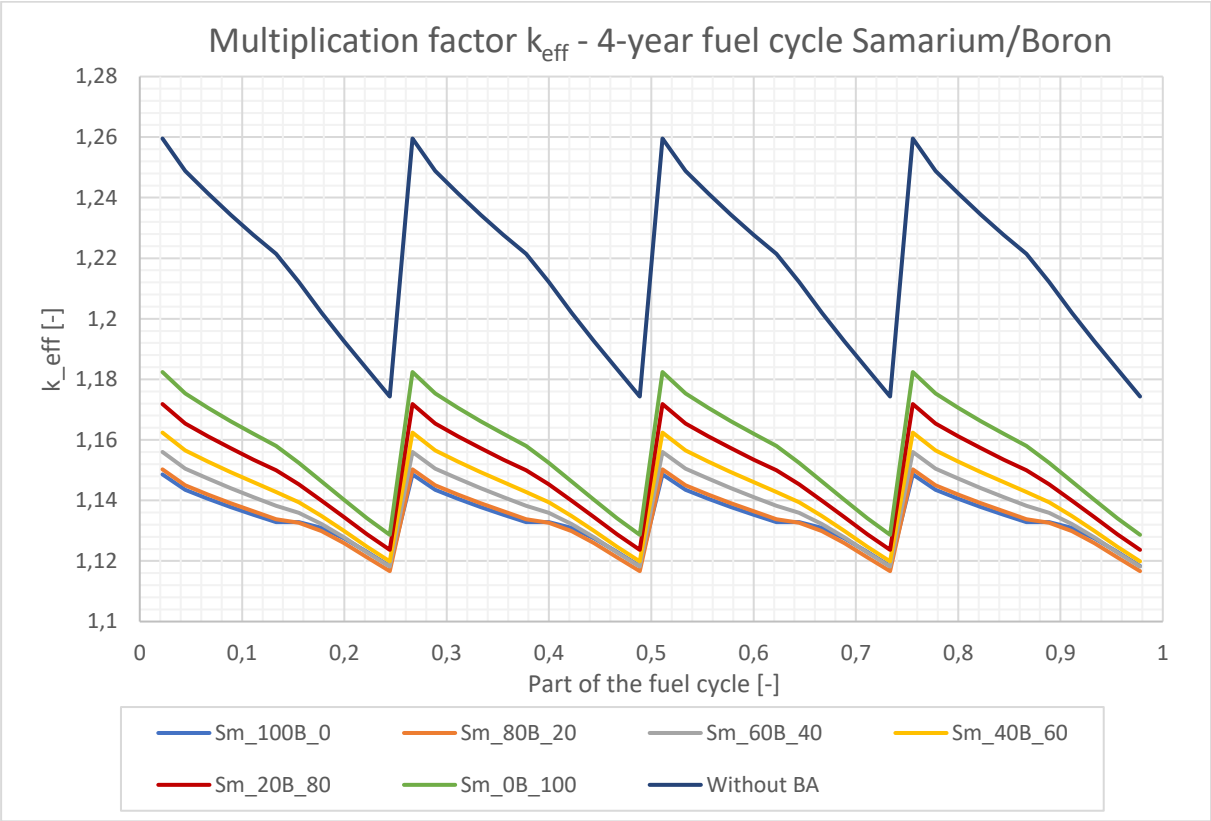


Graph 42. Multiplication factor (3-year fuel cycle) - Samarium/Boron

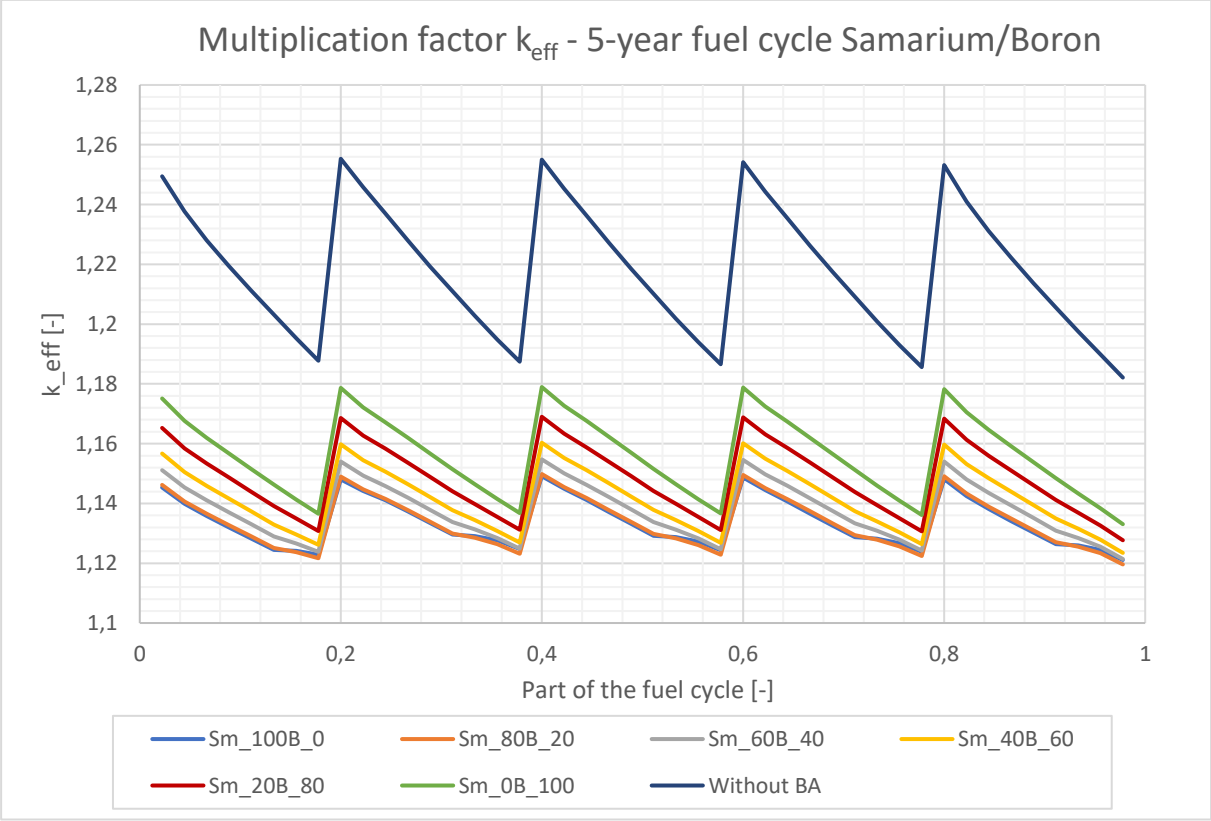
In the Graph 43, it can be seen, that the initial compensation in the 4-year fuel cycle is better than in the 3- year fuel cycle. Otherwise, the shape of the curves is similar in both cases. Again, due to the shorter individual parts of the fuel cycle, the first half of the curve is longer, thus the samarium working part is longer. At the end of each part, the curves of individual concentration are close together, but not as much as in the previous case, or in the case of gadolinium/boron combination.

For the 5-year fuel cycle (Graph 44), the initial compensation of reactivity is even better and as described in the cadmium/iridium part, the peaks are lower than in the previous cases. From the graph, it can be seen, that a larger part of the curve takes the part where samarium works. At the end, there can be found the attempt of the curves to end close together but due to the large part of the samarium, it is not that good.

Overall it can be said, that for the best initial reactivity compensation it is reasonable to use the 5-year fuel cycle. But, the end of the individual part is better in the 3-year fuel cycle, thanks to the fact, that all the concentrations are near together.



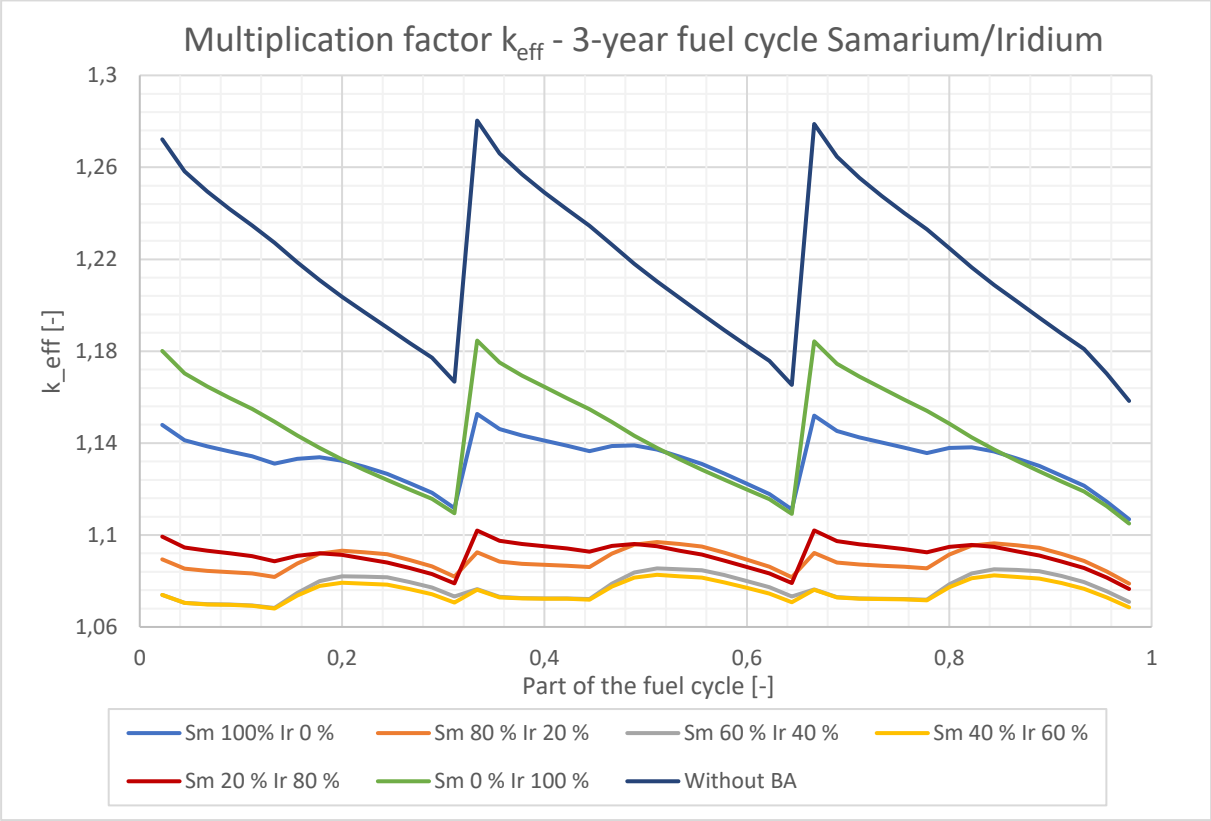
Graph 43. Multiplication factor (4-year fuel cycle) - Samarium/Boron



Graph 44. Multiplication factor (5-year fuel cycle) - Samarium/Boron

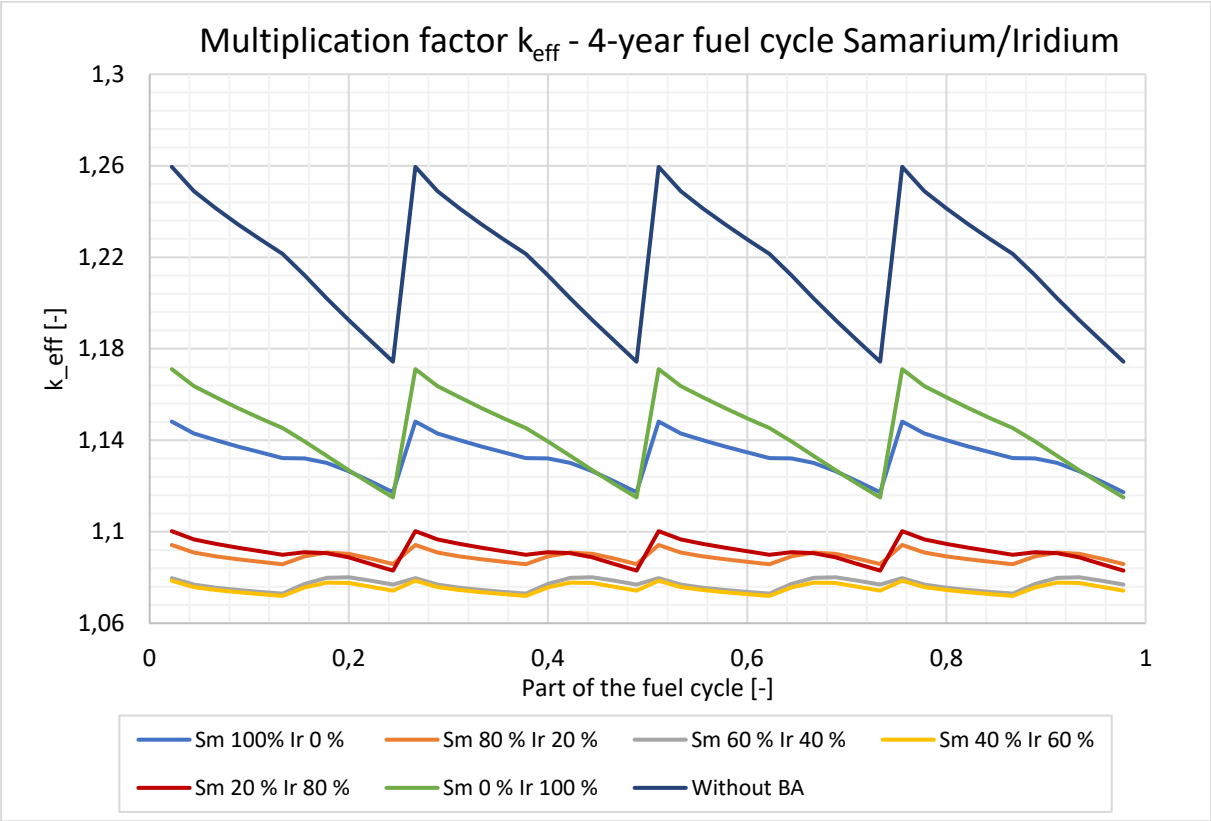
Samarium/Iridium

As the last combination that was appropriate for the use as a burnable absorber, the combination of samarium/iridium was selected. In this combination, the samarium was used as the fast burnable absorber and the iridium as the slow absorber. The multiplication factor behavior can be found in the following graphs.



Graph 45. Multiplication factor (3-year fuel cycle) - Samarium/Iridium

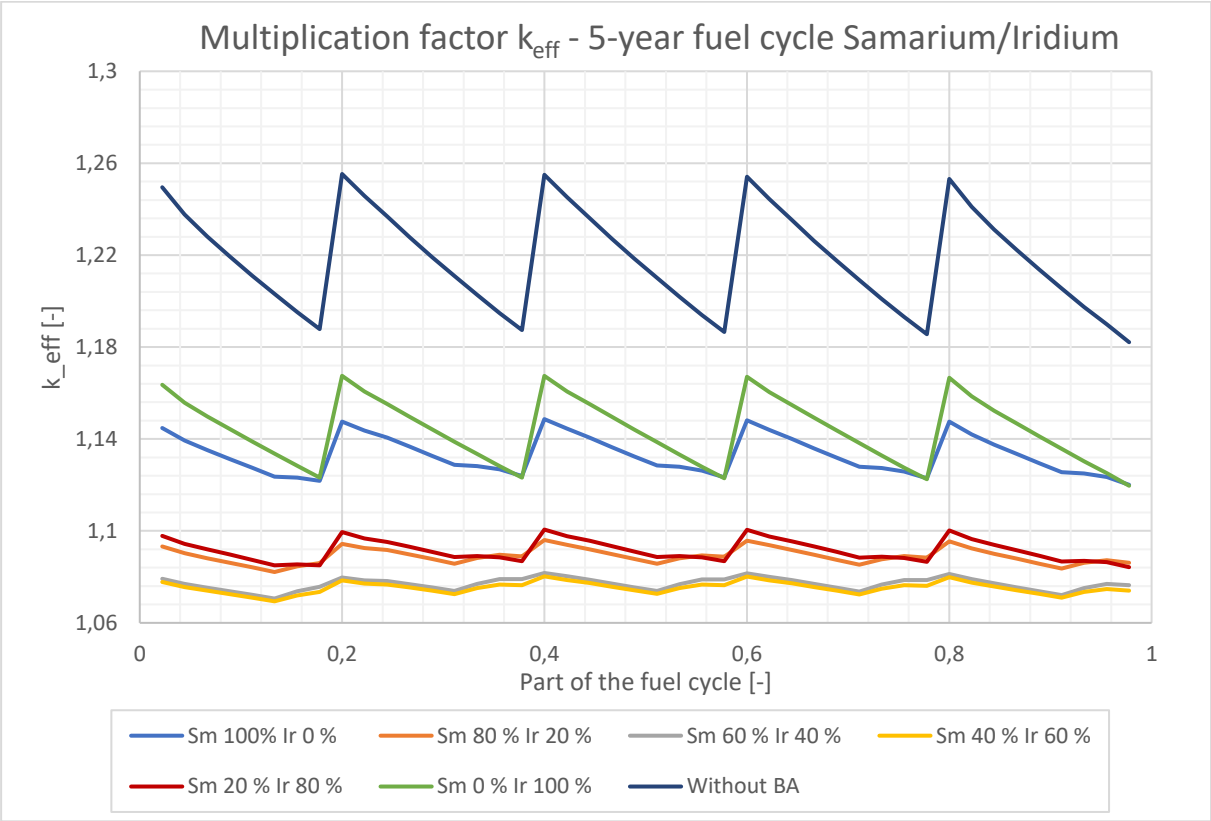
Regarding the 3-year fuel cycle shown in Graph 45, it can be observed, that the graphs are divided into three parts. The first part is the blue and green curves, which are the curves with single element BA, either 100 % of Sm or 100 % of Ir. The second part, where the reactivity compensation is significantly better, represents the red and orange curves. Then there is the last part with the yellow and grey curves, where the compensation is even better and the peaks between individual parts of the fuel cycle are barely there. These two last concentrations, specifically 60% Sm, 40 % Ir and 40 % Sm, 60 % Ir, can be labeled as the best ones. The behavior in this combination is totally different than in the combinations with boron as a slow burnable absorber.



Graph 46. Multiplication factor (4-year fuel cycle) - Samarium/Iridium

In the 4-year fuel cycle (Graph 46), slightly better reactivity compensation can be observed, but moreover, the behavior looks very similar. The best reactivity compensation is when the concentrations of 60 % Sm, 40 % Ir or 40 % Sm, 60 % Ir are used. In these two concentrations, the peaks are very low and the curves are overall very smooth. This smoothness of the curves gives the opportunity to use less amount of boric acid because there is no need to compensate the fluctuations of multiplication factor between the fuel changes.

For the 5-year fuel cycle, the situation is like the 3 or 4-year fuel cycle. The compensation is again slightly better and the peaks are barely visible. So, the use of boric acid could be decreased as well. Since the graphs are divided into three parts with different reactivity compensation, the design of the core could be easier. The whole core could be designed by just changing the concentration of each element in the combination, to be the best suitable for the particular part of the core.



Graph 47. Multiplication factor (5-year fuel cycle) - Samarium//Iridium

8. Evaluation

Once the calculation of each combination was done, it was necessary to make the evaluation. The evaluation was made according to 5 chosen parameters. The first parameter, that was used for the evaluation was the multiplication factor difference at the beginning of the fuel cycle. In the case of this parameter, it is desirable that the value is as large as possible, but it is necessary that the value is above $k_{eff} = 1$ or just a little bit below. Multiplication factor difference at the end of the fuel cycle was set as the second parameter. This parameter should be as close as possible to the case where none burnable absorber is used, or it should be above this curve. If it is above, it's even better, because the positive reactivity is released and the fuel cycle can be prolonged. Third parameter in this evaluation was the peak difference parameter. This parameter was calculated as the difference of the multiplication factor at the beginning of one part of the fuel cycle and at the end of it. For this parameter it is appropriate, that the value is as low as possible. If this value is low, the fluctuations in the multiplication factor between the fuel changes are low, thus it is not necessary to use as much of boric acid as it would be in the case without BA. The difference between the peaks without and with the burnable absorber was chosen as a fourth parameter. This parameter describes the reactivity compensation of mean values; thus, it is desirable, that this value is as large as possible. If this value is large, it means that the reactivity compensation is better. Final parameter chosen for this evaluation is the concentration of the burnable absorber in the fuel. It is obvious that smaller amount of burnable absorber means more space for uranium in the fuel and thus bigger burnup would be possible. The final evaluation can be found in table. The desirable value from this evaluation should be as low as possible.

After the selection of the parameters the evaluation was made. From this evaluation two best combinations came, specifically the combination of gadolinium/boron and samarium/iridium. Both combinations have great properties. The gadolinium/boron combination provides large initial reactivity compensation and then the curves start to converge together. This feature could be used in the design of the core. On the other hand, this combination has rather large peaks between the individual parts of the fuel cycle. The other combination, samarium/iridium, has also great initial reactivity compensation and, compared to the gadolinium/boron combination, the peaks, in this case, are barely there. This enables use of a

lower amount of boric acid for the reactivity compensation between the fuel changes. The disadvantage of this combination is bigger concentration needed than in the case of gadolinium/boron combination.

Table 6. Evaluation results

Combination	Cd/B					
Concentration of each element	100 %/0 %	80 %/20 %	60 %/40 %	40 %/60 %	20 %/80 %	0 %/100 %
Result	1,82E-02	1,92E-02	2,23E-02	2,77E-02	3,55E-02	4,63E-02
Combination	Sm/B					
Concentration of each element	100 %/0 %	80 %/20 %	60 %/40 %	40 %/60 %	20 %/ 80 %	0 %/ 100 %
Result	2,27E-02	2,57E-02	2,96E-02	3,42E-02	4,01E-02	4,64E-02
Combination	Gd/B					
Concentration of each element	100 %/0 %	80 %/20 %	60 %/40 %	40 %/60 %	20 %/80 %	0 %/100 %
Result	2,42E-02	2,69E-02	3,13E-02	3,58E-02	4,10E-02	4,66E-02
Combination	Cd/Ir					
Concentration of each element	100 %/0 %	80 %/20 %	60 %/40 %	40 %/60 %	20 %/80 %	0 %/100 %
Result	1,78E-02	9,29E-03	7,13E-03	9,97E-03	2,00E-02	4,86E-02
Combination	Sm/Ir					
Concentration of each element	100 %/0 %	80 %/20 %	60 %/40 %	40 %/60 %	20 %/80 %	0 %/100 %
Result	2,33E-02	5,05E-03	1,32E-03	2,38E-03	1,16E-02	4,90E-02

As the best combination was selected the combination of samarium/iridium. This combination has the lowest peaks from all the examined combinations and it has a good initial reactivity compensation as well. Another great feature of this combination is the fact, that the multiplication factor graph is divided into three parts with different reactivity compensation. This could be used in the design of the core. The concentration that compensates the reactivity less can be used in the part of the core, where the neutron flux is not that large. Even though this combination needs a larger concentration in the fuel, the positives outweigh this little problem, and it can be concluded this combination is the best.

9. Conclusion

The aim of this thesis was to find the optimal burnable absorber for the EPR reactor. It was necessary to make the research focused on burnable absorbers, their types and the EPR reactor. Then, further research about the elements that can be used for the following calculation was made. It is desirable that the elements, used as burnable absorber have large absorption cross section. Also, the daughter nuclide, created by absorption of a neutron, needs to have a smaller cross section. Eleven elements that meet this condition were selected. Namely Boron, Cadmium, Dysprosium, Erbium, Europium, Gadolinium, Hafnium, Lutetium, Iridium, Mercury, and Samarium. Another part of the process was to get familiar with the UWB1 depletion code. Once this was accomplished, an initial step calculation started. The initial step calculation was made for the fresh fuel. This calculation provided results about reactivity compensation in the first step when individual selected elements are present in the fuel. From evaluating these calculations, 6 elements were selected for further examination. Those elements are Boron, Cadmium, Dysprosium, Gadolinium, Iridium, and Samarium. For these six elements, detailed calculation was done, then the multiplication factor behavior and reactivity behavior graphs were made. Those graphs can be seen in chapter 6.3 Detailed calculation of six chosen elements.

Since the title of this thesis is EPR burnable absorber optimization, further steps of the process were pointed in the direction of double element burnable absorber. The idea behind double element burnable absorber is that one element is fast burnable absorber and the other one is slow. To make such a burnable absorber, it was needed to divide the elements into fast and slow BAs. The fast burnable absorbers were; Gadolinium, Cadmium, and Samarium. Opposite, the slow BAs were; Boron, Iridium, and Dysprosium. After this division, 9 combinations each containing always one slow BA and one fast BA were made. These 9 combinations were calculated, the results were examined and put into graphs. Those graphs can be found in chapter 7.1 Calculation of individual combinations. The last part of the calculations describes the usage of chosen combinations in a different length of the fuel cycle. Specifically, the 3, 4 and 5-year fuel cycle.

The final part of this work was an evaluation of the calculated values. The parameters for evaluation were set, 5 parameters in total; multiplication factor difference at the beginning of

the fuel cycle, multiplication factor difference at the end of the fuel cycle, the peak difference, the difference between the peaks without and with the burnable absorber and the concentration of BA. From this evaluation, emerged as the best combination, the combination of samarium/iridium. Therefore, this combination is the most suitable one for the EPR.

This thesis describes the usage of double element burnable absorber. The use of double elements burnable absorber allows the prolongation of the fuel cycle, the possibility to use less boric acid and to lower the concentration of burnable absorber. If the concentration of BA is lowered, the concentration of uranium can be increased. This would have an impact on the economy of the fuel. All elements used in this thesis were natural elements. For further research, the elements can be enriched with isotope, that has the largest cross section. With this enrichment, the results can be even more promising.

The results calculated in this thesis look good, but there is still a long way to go before this solution can be used in the real operation. This thesis is the first study of this problem made by fast depletion code. For future research, the calculation using macro codes would need to be done. Once this calculation would have been done, the research about the materials of selected combination would need to start. Nevertheless, this thesis can serve as a first glance at the idea of using two elements together in a burnable absorber.

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